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HUMAN RESPONSE TO NUCLEAR AND ADVANCED TECHNOLOGY WEAPONS EFFECTS

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May 1996

Final Technical Report for the Period January to December 1995

Approved for public release; distribution is unlimited.

AIR FORCE MATERIEL COMMAND
BROOKS AIR FORCE BASE, TEXAS

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The purpose of this study is to help the system survivability analyst estimate hardness requirements for systems exposed to nuclear weapons and advanced technology weapons (ATWs). The system survivability analyst is often asked to make quick, order-of-magnitude estimates on the hardness requirements for existing or proposed systems based upon human responses to the effects of nuclear weapons and ATWs. While the analyst may have training in mathematics or engineering, few have specific training in human response to ionizing and non-ionizing radiation. As a result, system survivability analysts have had difficulty answering mission survivability questions that are related to human survivability. The intent of this report is to identify the general range of human survivability to nuclear weapons and ATWs and to provide simple example calculations and scenarios that can give the reader rough estimates of the effects of these weapons. While high-powered microwave (HPM) and laser weapons are considered in this report, the main emphasis is on nuclear weapons and their ionizing radiation effects.

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1. INTRODUCTION

The purpose of this study is to help the system survivability analyst estimate hardness requirements for systems exposed to nuclear weapons and advanced technology weapons (ATWs). The system survivability analyst is often asked to make quick, order-of-magnitude estimates on the hardness requirements for existing or proposed systems based upon human responses to the effects of nuclear weapons and ATWs. While the analyst may have training in mathematics or engineering, few have specific training in human response to ionizing and non-ionizing radiation. As a result, system survivability analysts have had difficulty answering mission survivability questions that are related to human survivability. The intent of this report is to identify the general range of human survivability to nuclear weapons and ATWs and to provide simple example calculations and scenarios that can give the reader rough estimates of the effects of these weapons. While high-powered microwave (HPM) and laser weapons are considered in this report, the main emphasis is on nuclear weapons and their ionizing radiation effects.

Chapter 2 deals with nuclear weapon effects, principally the effects of ionizing radiation. The first section of the chapter reviews the basics of radiation biophysics as they apply to ionizing radiation. Subsections on radiation effects and dosimetry and on the biology of radiosensitive tissues and organs provide background on the biological effects of radiation. A subsection on acute radiation syndrome (ARS) provides the data on human response to different levels of radiation exposure that are critical for the analyst in determining mission survivability. A subsection on treatment gives recommendations for handling external and internal contamination and external exposure. The last section of Chapter 2 has subsections on blast overpressure, the effects of thermal radiation, and the effects of ionizing radiation (prompt and fallout).

Chapter 3 begins with a very brief introduction to non-ionizing radiation to help the reader understand the other sections in the chapter. The following section on HPMs is divided into three main subsections: a brief discussion of the physical characteristics of microwaves; a discussion of biological effects, which includes equations for calculating the depth of the microwave thermal effect; and some data on occupational limits. The last section of Chapter 3 is on lasers. This section mirrors the organization of the section on HPMs, but contains additional subsections on useful calculations and on different filtering methods for protection against laser weapons.

Chapter 4 is designed to give the reader a better understanding of how to determine human effects for several hypothetical scenarios involving ionizing radiation, high-powered radar, and lasers. The AF systems addressed in these scenarios include strategic and tactical aircraft, ground systems, and mobile launchers. The chapter shows the analyst

how to work through a problem by using information from Chapters 2 and 3. The discussion includes several simple calculations.

Chapter 5 is the conclusion of the report. The chapter is followed by some useful conversions displayed in tabular form, a list of definitions for all the acronyms and abbreviations, an extensive glossary of technical and medical terms, and a list of references.

2. NUCLEAR WEAPONS EFFECTS

This chapter reviews the basic characteristics of nuclear weapons effects. The effects considered here are blast overpressure, thermal radiation, and ionizing radiation. The blast overpressure and thermal radiation sections describe briefly human response to such effects. In order to better understand the effects from ionizing radiation or prompt radiation and fallout, this chapter begins with an in-depth review of the biological effects of ionizing radiation.

BIOLOGICAL EFFECTS OF IONIZING RADIATION

The biological effects of ionizing radiation have been well researched during the last several decades. This section provides the most current quantification of biological effects that are accepted by the health physics community. The first subsection provides a very basic background on qualitative ionizing radiation effects and basic dosimetry. The second subsection lists several of the most radiosensitive tissues and organs, explains why such tissues and organs are radiosensitive, and gives dose effects for each. The third subsection explains the acute radiation syndrome in detail, while the fourth subsection gives a brief discussion of exposure treatment.

Radiation Effects and Dosimetry

The biological effects of radiation depend upon the type of radiation, the absorbed dose, and how large a part and what part of the body is exposed. Biological effects are classified as either somatic or genetic. Somatic effects are those that occur in the exposed individual, whereas genetic effects are those that occur in the exposed individual's descendants. Since genetic effects are not mission-critical, only somatic effects will be discussed in this report.

Table 2-1 shows radiation effects for the different levels of biological organization. Although most of these levels will be mentioned in this report, the main emphasis is given to radiation effects on the whole organism because these are the effects that have the most impact upon a mission.

Radiation damage depends upon the absorption of energy. This damage is approximately equal to the concentration of the absorbed energy in tissue. The most basic unit of radiation dose is expressed in terms of absorbed energy per unit mass of tissue. This unit, the gray (Gy), is defined by the following equation:

$$1\ \text{Gy} = 1\ \text{J/kg} \tag{2.1}$$

The gray is applicable to all forms of ionizing radiation dosimetry. External exposure is often given in units of the roentgen (R). The following equation converts exposure in roentgens to absorbed dose (D) in gray:

$$D(Gy) = 8.77 \times 10^{-3} * [\mu_t / \rho_t] \div [\mu_a / \rho_a] * X \quad (2.2)$$

where X is the exposure in R, μ_t is the absorption coefficient in tissue, ρ_t is the density of tissue, μ_a is the absorption coefficient in air, and ρ_a is the density of air.

Table 2-1. Types of Radiation Damage (Severa, 1991)

Level of Biological Organization	Radiation Effect
Molecular	Impairment of the integrity of macromolecules such as enzymes, ribonucleic and deoxyribonucleic acids; derangement of metabolic processes
Subcellular	Damage to cellular membranes, cell nuclei, chromosomes, mitochondria, and lysosomes
Cellular	Blocking of cell division; cell death; malignant transformation of cells
Tissue, organ	Systemic breakdown (blood- forming tissue, gastrointestinal tract, central nervous system), with possible lethal outcome; induction of malignancy
Whole organism	Death; shortening of life span
Population	Alterations in genetic characteristics due to gene and chromosomal mutations in individuals; increased incidence of cancer

Occupational limits are often listed in terms of the dose equivalent (H), which is expressed in units of the sievert (Sv). The dose equivalent is the multiple of the absorbed dose (D) by a quality factor (QF):

$$H(Sv) = D(Gy) * QF \quad (2.3)$$

The quality factor is a normalizing factor, which was developed for health physics purposes in order to compare different types of radiation. As an example, neutrons and

alphas produce much greater effects than gamma and X rays given the same amount of energy absorbed. Table 2-2 lists several quality factors. It is also important to note that, for acute doses (i.e., absorbed doses over 1 Gy within 1 wk, it is not possible to express the dose in terms of the dose equivalent. This discrepancy arises because of the lack of knowledge concerning the biological effects of high energy radiation. This uncertainty does not permit the precise determination of numerical values for the quality factor.

Table 2-2. Quality Factor Values for Various Radiations
(Cember, 1987, and NCRP, 1991)

Radiation		QF
Gamma rays from radium in equilibrium with its decay products (filtered by 0.5 mm platinum)		1
X rays		1
Beta rays and electrons of energy > 0.03 MeV		1
Beta rays and electrons of energy < 0.03 MeV		1.7
Neutrons	<10 keV	5
	10 keV - 100 keV	10
	>100 keV - 2 MeV	20
	>2MeV - 20 MeV	10
	20 MeV	5
Protons		10
Alpha rays		20
Heavy ions		20

Another dose term is used to express one of the most important radiation effects, mortality. The term used to describe this effect is called the lethal dose (LD_X), where x is the percentage of occurrence for lethality within 60 d. Sometimes the LD_{50} is referred to as the mean lethal dose. The term *lethal dose* can also be used to describe effects to a tissue or organ, as well as whole body. Values for the lethal doses are discussed in the ARS section of this report.

Biology of Radiosensitive Tissues and Organs

This portion of the report is designed to provide the analyst with a basic understanding of how different parts of the body have different radiosensitivities and what the implications of this are. Tissues and organs with relatively high radiosensitivities are of interest because they represent the soft targets for determining the maximum permissible radiation doses. The following organs will be discussed in this section: skin, testes, ovaries, and lens of the eye.

In skin, the location of the target cells for carcinogenesis is within the basal membrane. The exact location of the basal membrane is questionable; it is generally accepted to be 70 μm, but the depth actually varies from 30–300 μm. This uncertainty makes skin-dose calculations indefinite.

Another issue to consider when performing skin dose-calculations is determining the exposed area over which the radiation dose should be measured. For external beam irradiation over relatively large exposed areas, one can use the entire skin organ as receiving the dose. However, exposure due to hot particles (i.e., radioactive particles less than 2 mm) requires more consideration. The National Council on Radiation Protection and Measurements (NCRP) has recently published a report on this issue (NCRP 1989). If one is required to perform such hot particle dosimetry, it would be best to seek this report as a guideline for calculations.

The most obvious effect of radiation damage to the skin is erythema. There are three phases of radiation-induced erythema. The first phase has a threshold of 3 – 6 Gy and appears as reddening within a few hours of exposure, peaks at 24 h, and then subsides after 2–3 d. The second phase is a wave of erythema beginning at 8 d, peaking at 14, and subsiding after a month. Finally, the third phase may occur beginning at 35 d. This phase is a reaction to the loss of epidermal cells and results in a reduction in the epidermal thickness (Mossman, 1992).

The maximum allowable occupational skin dose per year is 0.5 Sv, with a total lifetime limit of 20 Sv (NCRP 1987). These values, however, are currently under debate. Newly released information indicates that these limits may need to be lowered in order to reduce skin cancer risk (Mossman, 1992).

In the testis, spermatogenesis is similar to keratinocyte differentiation in that a basal membrane of stem cells gives rise to cells that differentiate as they move to the surface. Spermatogenesis differs in that the terminally differentiated sperm cells are alive and, therefore, present an additional potential target for radiation effects (Mossman, 1992).

Radiation affects the rate of production of differentiating cells from the stem cells. It also affects the yield of sperm produced from the spermatognium. Stem cells have an approximate mean lethal dose of 3 Gy. Cells that have completed meiosis, such as spermatozoa and spermatids, are less sensitive to the lethal effects of radiation than spermatogonia. Due to the resistance of these cells nearing completion of the differentiation process, infertility does not usually appear until 6 wk postirradiation (Mossman, 1992). The annual maximum permissible occupational dose to the testis is 0.5 Sv.

In the ovary, the oocytes are the target cells for radiation-induced sterility in females. This differs from that of spermatocytes in males in that these cells are not dividing. The mean lethal dose for oocytes has been estimated to be 0.12 Gy, making them the most sensitive cell type in the body. For females, the dose resulting in sterilization is age dependent. A woman in her forties may become permanently sterile after receiving an ovarian dose of 5–7 Gy; whereas, it would take a dose of 12–50 Gy to produce the same effect on a woman in her twenties. Typically, a dose of 3–4 Gy causes long periods of amenorrhea followed by recovery. A dose of 20–30 Gy causes high levels of gonadotropins as the body tries to stimulate the dysfunctional ovaries into estrogen production (Mossman, 1992). The annual maximum permissible occupational dose to the ovary is 0.5 Sv or an effective whole body dose of 0.05 Sv, whichever is lower.

As a tissue, the eye is unusual in two respects. First, it has no blood supply. Second, there seems to be no mechanism for removal of dead cells. Another unusual aspect of the eye is that radiation-induced cataracts develop differently from naturally occurring cataracts. This is distinct from most other radiation effects, which usually cannot be distinguished from the natural environment.

Cataractogenesis appears to be a nonstochastic effect (i.e., a nonrandom process with an intensity proportional to dose and with a threshold); this is different from most other biological effects of ionizing radiation. In humans, the threshold for producing cataracts is about 2 Gy; however, fractionation of the dose (i.e., fragments of the total dose are delivered over a short period of time) will lessen the effect and increase the threshold by a factor of at least two-fold. For an acute dose of 7.5 Gy, there is virtually a 100% incidence of cataracts, while fractionation of the dose will reduce the incidence to approximately 60%. Doses in the range of 2.5–6.5 Gy have a latency period of about 8 yr. The annual maximum permissible occupational dose to the lens of the eye is 150 mSv (NCRP 1987).

Acute Radiation Syndrome

Following a dose of 1 Gy or greater (i.e., an acute dose), one would expect several responses that vary directly with the amount of dose received. These responses are called acute radiation syndrome (ARS) and occur in several stages. The first phase of ARS is the

prodromal phase that lasts from 1–7 d. Many different symptoms are associated with the prodromal phase. The following is a list of such symptoms given in approximate order of increasing severity: anorexia, nausea, vomiting, weakness and fatigue, prostration, diarrhea, conjunctivitis, erythema, hypersthesia, paraesthesia, shock, oliguria, ataxia, disorientation, coma, and death. The next phase is the latent phase that lasts from 7–21 d. Next is the critical phase that occurs from the 2nd wk or 3rd wk up to the 7th wk. The following symptoms are those for the critical phase of ARS: fever, abdominal pain, abdominal distention, scalp pain, epilation, infection, purpura, hemorrhage, and weight loss. Finally, recovery or death occurs in 8–15 wk. Table 2-3 summarizes the phases and time frames for ARS, while Table 2-4 shows the time until the onset of prodromal symptoms and death for various doses.

Table 2-3. Phases of ARS

ARS Phase	Time Frame Postsexposure
Prodromal	1–7 d
Latent	7–21 d
Critical	2nd–3rd wk up to 7th wk
Death or Recovery	8–15 wk

Besides chronological order, it is also convenient to break ARS into several categories of response. The three main categories in order of increasing severity are the hematological syndrome, the gastrointestinal syndrome, and the neurovascular syndrome. A fourth syndrome has recently been discovered, the pulmonary syndrome. Certain effects are common to all categories: nausea and vomiting, malaise and fatigue, increased temperature, and blood changes.

The hematological category of ARS is the least troublesome of the four categories. In the dose range of 0–0.25 Gy, virtually no clinical symptoms exist, but a slightly increased frequency of chromosome aberrations may be detected in lymphocytes. In the range of 0.25–1 Gy, either no symptoms exist or transient nausea occurs. It is also possible at this stage that lymphopenia occurs and may be accompanied by slight thrombopenia. Cytogenetic changes in lymphocytes are readily detected. Some studies have shown slight changes in the patient's electroencephalogram. In general, the hematological form is exhibited when the dose is in the LD_{50} range (3–4 Gy). The symptoms begin with the prodromal symptoms of nausea and vomiting for approximately 48 h; however, nausea and vomiting can occur after an exposure of only 1.5 Gy. Then a latent period occurs for

Table 2-4. Times Until Onset and Frequency of Symptoms[a]
(Based on IAEA, 1988, and Levin, 1993)

Dose (cGy	Time Until Onset of Prodromal Symptoms	Frequency of Vomiting and Nausea (%)	Time Until Death	Frequency of Death (%)
25–50	—	0	—	0
75–200	2–24 h	20–70	3 mo	10
210–400	1–48 h	10–80	1–3 mo	30–60
410–600	0.5–1 h	90–100	2–8 wk	60–90
610–1500	0–0.5 h	100	10–50 d	>90
1500–5000	0–0.5 h	100	0.5–14 d	100
>5000	immediate	100	0.5–2 d	100

a. Untreated adults

about 2 wk. After this stage, the degradation of blood formation is depicted by infection and hemorrhaging. The hemorrhaging may take several forms: petechiae, large areas of bruising, nose bleeding, blood in urine, feces, or vomitus, and internal bleeding in the abdomen, chest, or head. If nausea or vomiting as well as some blood count derangement occur within 2 d of exposure, then the likely outcome of the hematological syndrome will be minor. If, however, a notable aberration in the leukocyte and lymphocyte count occurs within 3 d of exposure, then the hematological syndrome will be severe (Mossman, 1992).

The gastrointestinal system begins showing a response to radiation at a higher level than the hematological system. Gastrointestinal effects begin showing at about 10 Gy. The prodromal symptoms of this form are likely to be more severe than the hematological form and also include diarrhea. The latent period is several days, after which gastro-intestinal irregularities can be detected. Such irregularities include bleeding in the gastrointestinal tract and signs of infection, malnutrition, and electrolyte imbalances. The major symptom of this form is loss of integrity in the gastrointestinal lining. The occurrence of diarrhea within 4 d of exposure and significant platelet degradation within 6–9 d of exposure are indicative of the presence of the gastrointestinal syndrome (Mossman, 1992).

The neurovascular form is the most intense form of ARS and occurs after an exposure in the range of 20–30 Gy. For this syndrome, nausea, vomiting, and diarrhea occur within

minutes. Ataxia, disorientation, shock, and coma occur in minutes to hours. The prodromal symptoms are accompanied by the state of consciousness ranging from apathy and lethargy to hyperexcitability, tremors, convulsions, and gait disturbances. Death occurs within hours up to 1 or 2 d (Mossman, 1992).

The pulmonary form is typically seen in therapeutically irradiated patient. However, it was also diagnosed in seven Chernobyl accident patients. The threshold dose range for this category is around 8 to 9 Gy. Interstitial edema and respiratory failure may occur within 3 d, or interstitial pneumonitis may occur 14–30 d postirradiation (Mossman, 1992).

Finally, another way to break down the symptoms of ARS is by dose received. The following discussion describes what occurs for varying doses in increasing order. For doses in the range of 1–2 Gy, ARS takes a mild degree of the hematopoietic form. Nausea and vomiting occur in only a fraction of the irradiated persons. The symptoms occur in the first hours after exposure. Development of neutropenia and thrombopenia takes 4–6 wk. This degree of cytopenia usually does not lead to bleeding and infection. The majority of the patients recover without treatment. However, to prevent infection and hemorrhagic symptoms, careful hematological follow-up and care are required (IAEA, 1988).

Doses in the range of 2–4 Gy yield a moderate degree of the hematological syndrome. Nausea and vomiting appear after 1–2 h. In most victims, the lowest point of neutropenia and thrombopenia develops in 3–4 wk. In all patients, these symptoms are accompanied by fever and bleeding. If the exposed person is given medical treatment, the chances of a full recovery are about 90%. Without medical treatment, mortality can be as high as 50% (IAEA, 1988).

Doses of 4–6 Gy produce a severe response. Nausea and vomiting appear 0.5–1 h after irradiation. Other prodromal symptoms are manifest: early fever, erythema of skin, and mucosae. The deepest fall in the number of neutrophils and thrombocytes occurs at 2–3 wk and very low values are reached. The latter are maintained for a period of about 2 wk. Without therapy, the majority of patients will die of infections and the consequences of bleeding. If adequate supportive therapy is instituted, the majority of patients are likely to recover (IAEA, 1988).

For doses in the range of 6–10 Gy, extremely severe hematopoietic syndrome occurs. Nausea and vomiting appear very early, less than 30 min after exposure. In a substantial proportion of the victims, diarrhea occurs 1–2 h after the irradiation. Maximal cytopenia appears at 10–14 d. Also, at 6–8 d postexposure, acute radiation stomatitis becomes evident. Sometimes at 8–10 d after exposure, radiation-induced enteritis is seen. Without medical treatment, 100% of the people exposed to 6–10 Gy probably will die. If therapy, which will be discussed later, is applied soon after exposure, a fraction of the exposed population still may survive. The lethality results from the coincidence of severe impair-

ment of the hematopoietic function and radiation injury to other organs, mostly of the pharyngeal mucosa, esophagus, and intestines. Injury to pulmonary tissue may also play a significant role (IAEA, 1988).

Table 2-5 shows the dose required to produce various health effects for 10% and 50% of the population. Table 2-6 shows the effects of doses fractionation on the mortality of exposed people. For prompt doses, use an exposure time of 1 wk to calculate the lethal dose. For fallout dose, use a time of 2 wk. In particular, Table 2-6 displays the lethal doses in 60 d for various percentages of the population. They are based upon the equation:

$$LD_{50} = (\text{lethal dose for 1 wk}) * t^{0.26} \qquad (2.4)$$

where t is the time duration of exposure in weeks.

Treatment

The purpose of diagnosing and treating accidentally exposed individuals is to mitigate the actual and the potential radiation damage. External contamination should be treated before internal contamination to prevent further spread of contamination. External irradiation may be of varying intensity and may affect different portions of the body or the whole body; it should be treated accordingly.

EXTERNAL CONTAMINATION

For external contamination, it is important to remove as much of the radionuclide as possible to reduce the surface dose rate and to prevent the contamination from being absorbed into the body. One must be careful not to be too aggressive in decontaminating the skin; otherwise, the skin may be injured, which could result in an increase in percutaneous absorption.

Since the physio-chemical nature of the compound is usually unknown at the time of the contamination, it may be necessary to use several agents to decontaminate the skin. Begin with the mildest agent and progress with more vigorous ones if the mildest agent doesn't work. An example of this method would be starting with ordinary soap and water, then an abrasive soap, followed by detergents, oxidizing agents such as sodium hypochlorite (e.g., household bleach), complexing agents (e.g., citric acid), and finally, if

Table 2-5. Acute Noncancer Effects of Radiation and Approximate Prompt Dose for 10% and 50% Incidence in People (Based on Mossman, 1992, and Schleien, 1992)

Irradiation[a]	Health Effect	Dose for 10% Incidence (cGy)	Dose for 50% Incidence (cGy)
Whole Body (external)	Anorexia	40	150
	Nausea	55	210
	Fatigue	55	220
	Vomiting	70	280
	Epilation	75	300
	Diarrhea	90	350
	Hemorrhage	100	400
	Death	110	345
Reproductive Organs (external)	Sterility:		
	males (temporary)	5	20
	males (permanent)	150	600
	females (temporary)	75	300
	females (permanent)	250	1000

a. Whole body dose for low LET radiation, such as gamma-ray radiation from fallout

necessary, chelating agents (e.g., ethylenediaminetetraacetic acid [EDTA] and diethylene-triaminepentaacetic acid [DTPA]). Ordinary soap and water should be sufficient to remove fallout contamination from skin and clothing.

Table 2-6. Approximate Lethal Doses for 10%, 50%, and 90% of the Population (Based on Schleien, 1992)

Time[a] (wk)	LD_{10} (cGy)	LD_{50} (cGy)	LD_{90} (cGy)
1	110	345	585
2	130	410	700
3	145	460	780
4	160	495	840
8	190	590	1005
24	250	790	1340

a. Duration of radiation exposure time

INTERNAL CONTAMINATION

The first step of internal decontamination is to treat any radionuclide-contaminated wounds. Such wounds should be rinsed with water or saline to remove as much of the compound as possible. Once this is done, treat the wound as appropriate. If internal deposition occurs, whether it be through ingestion or a wound, intervention to decrease the natural removal time will probably be advantageous to decrease the absorbed dose.

Internally deposited radionuclides may be removed by several methods: dilution, blocking, mobilization, and chelation. In the dilution method large quantities of the stable element are administered so that, statistically, the possibility for incorporation and exposure of the radionuclide is decreased. Blocking is a preventative method by which the agent saturates the metabolic process in a specific tissue with the stable element, thereby reducing the uptake of the radionuclide. Mobilization is a method that increases a natural turnover process and induces a release of some forms of radionuclides from body tissues. Chelation is actually a special class of mobilization. It is a process by which organic compounds exchange less firmly bonded ions for other inorganic ions to form a relatively stable non-ionized ring complex. This process converts the nuclides into a more soluble form that can then be excreted from the body. Table 2-7 shows some of the common agents used for these methods.

At this time, many decontamination agents are not available on the open market, but are available to qualified physicians through the Department of Energy as investigational drugs; they require written informed patient consent for use. At the same time, many radioprotectors are currently being developed. The following section describes a few radioprotectors that are under development.

Table 2-7. Decontamination Methods and Agents for Some Important Radionuclides (Mossman, 1992)

Method	Isotope	Agent
Dilution	^{3}H	Water
Dilution	^{32}P	Phosphorus (neutrophos)
Blocking	^{137}Cs	Ferric ferrocyanide (Prussian Blue)
Blocking	^{131}I, ^{99m}Tc	KI (Lugol's solution)
Blocking	^{89}Sr, ^{85}Sr	Al-phosphate (Phosphojel), Al-hydroxide (Amphojel), Na-Alginate (Gaviscon)
Mobilization	^{86}Rb	Chlorthalidone (Hygroton)
Chelation	^{252}Cf, ^{242}Cm, ^{241}Am, ^{239}Pu, ^{144}Ce, rare earths, ^{143}Pm, ^{140}La, ^{90}Y, ^{65}Zn, ^{46}Sc	DTPA
Chelation	^{210}Pb	EDTA, penicillamine
Chelation	^{203}Hg, ^{60}Co	Penicillamine

One investigational radioprotector, WR-2721, enhances survival by protecting cells from radiation-induced lethality through free-radical scavenging, hydrogen atom donation, induction of hypoxia, or combinations of these mechanisms. The cells best protected by WR-2721 are the hemopoietic stem and progenitor cells. Glucan helps to protect hemopoietic-type cells. The induction of edogenous oxidative substances, such as glutathione peroxidase, is the probable mechanism through which selenium exhibits its radioprotection. According to Patchen (1990), a combination of these three treatments produces synergistic radioprotection. The degree of protection and overall benefit of this combination has not been quantified.

Another investigational agent, WR-1065, has been shown to enhance DNA repair. Radioprotectants are believed to protect the genome by decreasing the supercoiling of DNA. WR-33278 stimulates topoisomerase I unwinding of the supercoiled state, and

hence provides the possibility of new mechanisms for radioprotective chemicals to invoke protection (Holwitt, 1990). Again, as with the previously mentioned investigational agents, the overall benefit of WR-1065 has not yet been determined.

Some radioprotectors are designed to target specific organs. WR-77913 is such an agent. This radioprotector has been shown to reduce cataract incidence in irradiated rat eyes when administered prior to irradiation (Mossman, 1992). Extrapolations of these data to human benefits have not yet been determined.

Another common treatment is to assuage the nausea and vomiting symptoms. The intragastric administration of the investigational antiemetic and gastrokinetic agent called zacopride significantly inhibits radiation-induced retching, vomiting, and suppression of gastric emptying in rhesus monkeys. Experimentation shows that it does not cause behavioral side effects (DuBois, 1988). Currently, thorazine, chlopromazine, and compzine are used as antiemesis drugs (Rics, 1993). Generally, such antiemetic agents show better results if administered before the onset of the radiation exposure.

EXTERNAL EXPOSURE

Supportive treatment can considerably increase the life expectancy of a person who has received a dose in the range of 2 to 5 Gy. There are four basic aspects of supportive treatment: the maintenance of a clean environment; prophylactic oropharyngeal and gastrointestinal antibiotic therapy; use of intravenous fluid, nutrients, and blood fractions; and vigorous therapy of infections.

For people who receive high external doses of radiation, say 6 Gy or more, the chances of dying are essentially 100% unless the patient receives heroic medical treatment. Heroic treatment is basically supportive treatment supplemented with a bone marrow transplantation. At levels of 8–10 Gy, the immune system is destroyed, so the transplant is more readily accepted. Hence, a person who receives a dose of 8 Gy and undergoes a bone marrow transplant has a greater chance of survival than one who receives a dose of 7 Gy. The latter individual's bone marrow is destroyed, but, because his immune system is not, he would likely reject a transplant. For persons receiving a dose greater than 10 Gy, even heroic treatment is futile.

NUCLEAR WEAPONS

Blast Overpressure

Blast injuries are divided into two classes, direct (primary) and indirect. The primary injuries derive from environmental pressure variations, whereas the indirect injuries arise from the impact of projectiles or as the result of whole-body displacement. Blast effects in

man from fast-rising, long-duration pressure pulses that were seen in the Hiroshima and Nagasaki exposures are displayed in Table 2-8.

There are four main systems of the body that have been studied to determine their response to blast overpressure. They are the respiratory system, solid organs, gastro-intestinal tract, and the auditory system. Damage to each of these systems is described below.

For the respiratory system, the lungs are the target organ; disruption permits air emboli to enter the bloodstream and cause rapid death. Lung hemorrhages range from a few pinhead-sized petechiae on the surface of the lung to the involvement of entire lobes with severe hemorrhaging. Severe blasts can rupture the lung itself or cause ribs to fracture and puncture lung lobes. In the upper air ways, the mucosal lining of the sinus, larynx, pharynx, and trachea can be bruised from low-level blasts. More intense blasts can cause hemorrhaging beneath the mucosa and reduce the size of the air passage (Levin, June 1993).

Table 2-8. Blast Effects in Man (Glasstone, 1977)

Health Effect	Effective Peak Pressure (psi)
Lung Damage:	
Threshold	8–15
Severe	20–30
Lethality:	
Threshold	30–50
50%	50–75
100%	75–115
Eardrum Rupture:	
Threshold	5
50%	15–20 (for age > 20)
	30–35 (for age < 20)

In the solid organs category, organs that are close to the lungs or the gastrointestinal tract are the organs likely to have damage. This damage could range from contusions to rupturing that is due to the overexpansion of gas

At lower blast overpressures, there are contusions to the serosa (outer layer) ofthe GI tract. As the overpressure increases, hemorrhaging occurs. The contusions may rupture, in which case the contents of the GI tract would enter the abdominal cavity, with an end result of peritonitis (Levin, June 1993). Table 2-9 shows exposure levels required to produce lung and GI-tract injuries.

Table 2-9. Estimated Long-Duration Blast Levels Required to Produce Lung and Gastrointestinal Tract Injuries to Prone Man End-On to the Blast at Sea Level (Levin, June 1993)

Injury Level	Overpressure (psi) Required to Produce Lung Injury	Overpressure (psi) Required to Produce GI-Tract Injury
None	10.3	7.0
Trivial	14.4	8.4
Slight	19.2	14.0
Moderate	29.0	23.6
Severe	34.3	29.4
Very Severe	42.0	37.4

At overpressures as low as 3 psi in the auditory system, the ear drum may suffer minor ruptures. At 8 psi and above, the ear drum will undergo complete rupture (Levin, June 1993).

Thermal Radiation

Immediately after the explosion, the weapon residues emit the primary thermal radiation. Due to the very high temperature, much of this is in the form of X rays that are absorbed within a layer of a few feet of air; the energy is then reemitted from the fireball as thermal radiation of longer wavelength consisting of ultraviolet, visible, and infrared rays. The first pulse may result in permanent or temporary effects on the eyes (especially to

individuals who happen to be looking in the direction of the explosion). The second radiation pulse may last for several seconds (10 s for 1 MT yield); this pulse causes skin burns of various degrees up to 12 mi or more and eye effects at even greater distances (for 1 MT yield). This pulse also starts fires.

The thermal exposure decreases with distance from the point of detonation as a result of the inverse square law. If an airbrust occurs above dense cloud, smoke, or fog, most of the thermal radiation will be reflected upward and little will reach the earth's surface. Conversely, if the airburst occurs below a cloud, the thermal radiation reaching the earth would be greater than on a clear day. A ground cover of snow can also intensify the thermal radiation.

Most thermal radiation (flash) burns are limited to uncovered areas of the skin that are facing the center of explosion. It is possible, however, for skin to be burned even through a layer of clothing; in such cases, the radiant exposure must be large enough to char the fabric. Skin that is burned while covered is actually burned by the fabric. A person wearing dark clothing has a higher risk of receiving a flash burn than one wearing light clothing, because the dark fabric absorbs more radiant energy (Glasstone, 1977).

Burns are classified according to their severity as either first, second, or third degree burns. A first degree burn involves only the epidermis and causes erythema and edema without vesiculation. A second degree burn involves the epidermis and dermis and usually forms blisters that may be superficial or deep dermal necrosis, but with epithelial regeneration extending from the skin appendages. A third degree burn involves the destruction of the entire skin; deep third degree burns extend into subcutaneous fat, muscle, or bone and often cause much scarring.

In addition to skin burns, thermal radiation may also cause either temporary or permanent eye damage. Temporary eye damage, also known as flashblindness, occurs when more thermal energy is received than is necessary for image perception, but is not enough to produce a retinal burn. Flashblindness is caused by a bleaching of the light-sensitive rods and cones in the retina of the eye. Flashblindness will typically hide the entire field of view with a bright afterimage. This effect lasts for only a short time (several seconds to minutes) and recovery is complete. Permanent eye damage (e.g., retinal burns) arises from the excessive heating of the retinal tissue. Since, the optical process of image formation within the eye keeps the energy per unit area on the retina constant, regardless of distance, the probability of permanent eye damage does not decrease as the square of the distance from detonation. Probability does, however, tremendously increase if a person looked directly at the fireball (Glasstone, 1977).

Ionizing Radiation

PROMPT RADIATION

Neutrons and gamma rays represent the main ionizing radiation hazards after a nuclear explosion. Almost all of the neutrons and part of the gamma rays are emitted in the actual fission process. These are referred to as the prompt nuclear radiations because they are produced simultaneously with the nuclear explosion. Generally, anything that emerges within the first minute is considered to be prompt radiation.

Gamma rays and X rays are electromagnetic radiation that have no mass and no charge and travel at the speed of light. Gamma rays have great ranges in air, whereas X rays have shorter ranges due to their lower energies. Neutrons have appreciable mass, no electric charge, and relatively great ranges in air, although this characteristic depends upon their energy. Alpha and beta particles are charged and travel at varying speeds depending upon their energies, but have relatively short ranges in air.

FALLOUT

Fallout is categorized into two parts, early and delayed. Early fallout, also called local, is that which reaches the ground during the first 24 h following a nuclear explosion. Delayed fallout, also called long range, reaches the ground after the first day. Delayed fallout consists of very fine, invisible particles that settle in low concentrations over a substantial portion of the earth's surface. The fallout radiation decays rapidly, and normal operations can be resumed in most areas within two weeks after the nuclear detonations.

The primary radiation hazards from fallout are beta and gamma radiation from the fission products in the weapon. Beta particles from fallout that lands on the skin can penetrate into the deeper layers of the skin. Because of this, the beta radiation is an external radiation hazard. Even moderate clothing will provide substantial protection against beta radiation, and then the beta radiation becomes primarily an internal radiation hazard. It is important to cover any cuts or abrasions in the skin, and to use respirators or gas masks to filter the air in a fallout environment.

From dose reconstructions of people who lived within a few hundred miles of the Nevada test site, four significant nuclides accounted for nearly 75% of the whole body internal dose from the fallout. These nuclides, in decreasing order of dose contribution, are ^{89}Sr, ^{90}Sr, ^{137}Cs, and ^{131}I. Inhalation doses are insignificant compared to external doses, with the exception of ^{131}I dose to the thyroid. In almost all cases of interest, the internal dose is a small fraction of the external dose received from fallout, which can range from several rem to several hundred rem, depending upon the weather and what kind of shelter the population is using (Peterson, January 1992). Other nuclides of significant dose

considerations are ^{14}C and ^{3}H. Minor dose contributions come from ^{85}Kr, ^{55}Fe, and ^{239}Pu (Moe, 1988).

Since the atomic cloud may reach heights of 30 mi or more, it may take the early fallout particles as long as 20 to 30 min to reach the ground. As a result, the starting exposure rates are assumed to begin at 1 h postexplosion to allow most of the early fallout particles to reach the ground.

Calculating the exposure rate can be approximated very easily once the exposure rate at 1 h postexplosion is known. One general rule of thumb for this is called the seven-ten rule. This rule states that for every sevenfold increase in time, as measured from the time of explosion, there is an approximate tenfold decrease in exposure rate (NCRP, 1974). For example, if 1 h past the time of explosion, the exposure rate is 1,000 R/h, then 7 h after explosion, the rate would be 100 R/h. Forty-nine hours postexplosion, the rate would be 10 R/h; 343 h (approximately 2 wk) after explosion, the exposure rate would be 1 R/h. A more precise approximation is given by:

$$d = d_1 * t^{-1.2} \tag{2.5}$$

where d is the exposure rate at time t, d_1 is the exposure rate 1 h past the time of explosion, and t is the time past explosion in hours. This equation is effective for time greater than 6–10 h after explosion.

As mentioned in the section on the biology of radiosensitive tissues and organs in this chapter, fractionation of the total absorbed dose decreases the negative health effects. Recall from Table 2-6 that the LD_{50} for 2 wk of exposure time (the recommended value for fallout exposure) is 130, 410, and 700 cGy for 10%, 50%, and 90% of the population, respectively.

3. ADVANCED TECHNOLOGY WEAPONS EFFECTS

This section of the report reviews the basic effects of ATWs. The weapons considered here are high-powered microwaves (HPMs) and lasers. A section on non-ionizing radiation provides a useful review to prepare the reader for the sections on ATWs. The HPM and laser sections show the human response to the effects of these weapons.

NON-IONIZING REVIEW

Two developments brought attention to the possible public health aspects of non-ionizing radiation. The first was the postwar boom in electronics and communications based on the microwave portion of the electromagnetic spectrum. This was shortly followed by the second development, the rapidly increased use of lasers. When discussing microwaves and lasers, it is important to have an understanding of the electromagnetic spectrum. Figure 3-1 shows a summary of the electromagnetic spectrum and lists some common lasers.

When discussing lasers in particular, it is also useful to understand the breakdown of the ultraviolet radiation (UVR) spectrum. The UVR spectrum may be divided into three major components that induce significantly different biological effects: a UV-A component with wavelengths from 400 nm to 320 nm (i.e., long wave UVR, near UVR, or black light); UV-B 320–280 nm (i.e., middle UVR or "sunburn" radiation); UV-C 280–200 nm (i.e., short wave UVR, far UVR, or germicidal radiation). Wavelengths below 200 nm are of little biological significance since radiation in this region ("vacuum UVR") is absorbed in very short pathlengths in air. The division of the UVR spectrum is shown in Figure 3-2.

HIGH-POWERED MICROWAVES

Research is currently being performed to determine if a cumulative effect can occur from microwave exposure. However, to date, epidemiological studies have not demonstrated any long-term consequences beyond those present at the time of the exposure. Since the cumulative-effect theory is at an investigational stage, this report will only consider thermal effects. The content of this section includes a basic microwave review, a discussion of biological effects, and tables of occupational exposure limits.

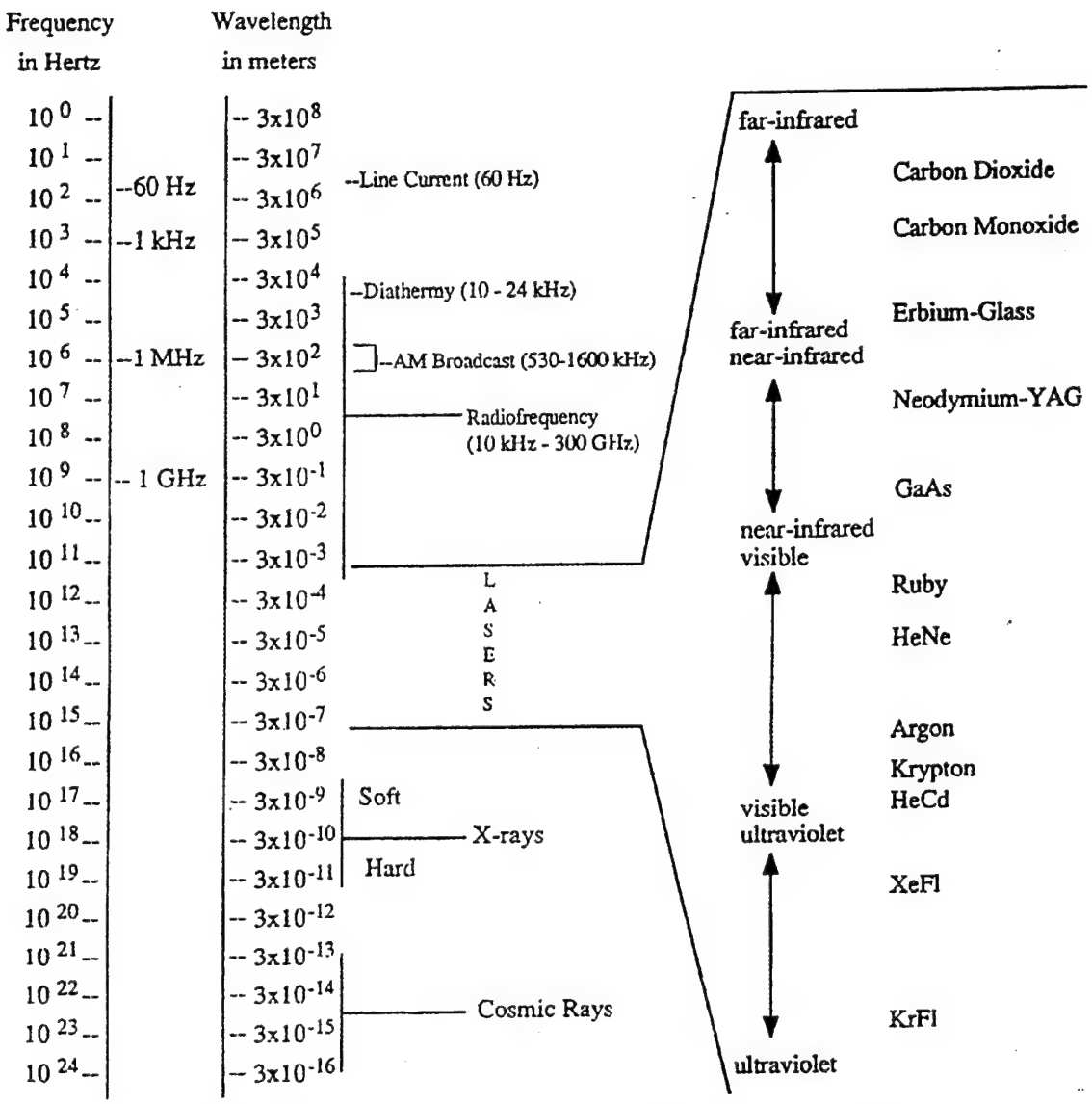

Figure 3-1. Electromagnetic Spectrum (Rademacher, 1992)

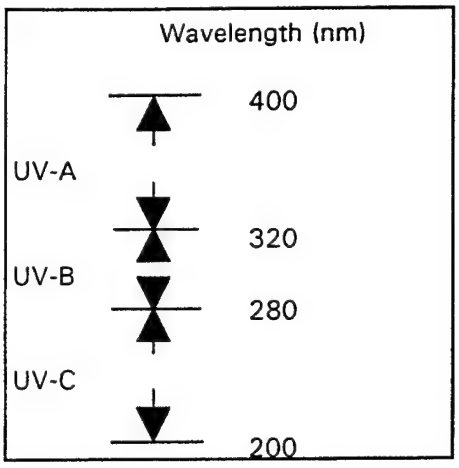

Figure 3-2. Ultraviolet Radiation Spectrum

Microwave Review

Microwaves (MW) are a non-ionizing form of electromagnetic radiation, ranging in wavelength from about 1 mm to about 1 m. Microwave frequency ranges from approximately 300 MHz to 300 GHz. The frequency bands that have been assigned to radar systems are listed in Table 3-1.

Table 3-1. Microwave Frequency Bands
(Cember, 1987)

Band	Frequency (GHz)	Wavelength (cm)
L	1–1.4	27.3–21.4
S	2.6–3.95	11.5–7.6
C	3.95–5.85	7.6–5.13
X	8.2–12.4	3.66–2.42
K_u	12.4–18	2.42–1.67
K	18–26	1.67–1.16
K_a	26–40	1.16–0.75

Microwave interaction with matter takes place in these forms:

- Reflection (as with metals)
- Transmission (as with glass)
- Absorption (as with tissue)

Microwaves typically interact with matter in all three ways; however, normally only one is predominant. When microwave energy is reflected, virtually no energy is lost. When it is transmitted, little energy is lost to the transmitting medium. When microwave energy is absorbed, however, much of the energy is lost in the form of heat to the irradiated matter. This heating is due to two effects. First, the main mechanism is believed to be joule heating due to ionic currents induced by the electric fields that are set up within the absorbing medium by the radiation. Second, the interaction between polar molecules in the absorber and the applied high-frequency electric field gives rise to some heating. This is due to the alternating electric field, which causes the polar molecules to oscillate back and forth to maintain the proper alignment in the electric field. Ultimately, the oscillations are resisted by other intermolecular forces, and the work done by the alternating electric field in overcoming these resistive forces is converted to heat (Cember, 1987).

Biological Effects

As microwaves pass through matter and lose energy, there is a continuous decrease in the intensity of the electromagnetic field. This decrease is related exponentially to the depth of penetration into the absorbing medium and is given by:

$$E_2 = E_1 * e^{-2\alpha t} \qquad (3.1)$$

where E_1 is the initial power density, t is the absorber thickness, E_2 is the power density at depth t, and α is the absorption coefficient. This absorption coefficient is dependent on the frequency of the radiation and on the conductivity, permitivity, and permeability of the absorber. The absorption coefficient can be calculated by the following equation:

$$\alpha = \omega * (0.5\mu\varepsilon)^{1/2} * \{[1 + (\sigma/\omega\varepsilon)^2]^{1/2} - 1\}^{1/2} \qquad (3.2)$$

where ω is the angular frequency given by $2\pi f$, σ is the conductivity in units of $(\text{ohm-meter})^{-1}$, ε is the permitivity, and μ is the permeability. Since the permeability of biological substances is very close to that of free space, $\pi = \pi_o = 4\pi x 10^{-7}\ N/A^2$ (Cember, 1987). Tables 3-2 and 3-3 show some of these electrical properties of muscle and fat.

Table 3-2. Electrical Properties of Human Muscle (Cember, 1987)

Frequency (MHz)	Wavelength in Air (cm)	Dielectric Constant	Conductivity (mho/m)	Depth of Penetration (cm)	Wavelength in Tissue (cm)
27.12	1,006	113	0.612	14.3	68.1
40.68	738	97.3	0.693	11.2	51.3
100	300	71.7	0.889	6.66	27
433	69.3	53	1.43	3.57	8.76
750	40	52	1.54	3.18	5.34
915	32.8	51	1.60	3.04	4.46
1,000	20	49	1.77	2.42	2.81
2,450	12.2	47	2.21	1.70	1.76

Table 3-3. Electrical Properties of Human Fat (Cember, 1987)

Frequency (MHz)	Wavelength in Air (cm)	Dielectric Constant	Conductivity (mho/m)	Depth of Penetration (cm)	Wavelength in Tissue (cm)
27.12	1,006	20	10.9–3.2	159	241
40.68	738	14.6	12.6–52.8	118	187
100	300	7.45	19.1–75.9	60.4	106
433	69.3	5.6	37.9–118	26.2	28.8
750	40	5.6	49.8–138	23	16.8
915	32.8	5.6	55.8–147	17.7	13.7
1,000	20	5.6	70.8–171	13.9	3.41
2,450	12.2	5.5	96.4–213	11.2	5.21

In biological tissue, the rate of heat being produced is inversely proportional to the square of the penetration depth. Therefore, a tissue with a relatively small penetration depth because of high water content will heat much faster. An example of this tissue type is muscle. A tissue with a relatively large penetration depth because of lower water content will heat more slowly. An example of this tissue type is fat (Cember, 1987).

Radiation dosimetry involves the measurement of the power and energy that are absorbed by the internal organs of a biological subject when subjected to external radiation exposure fields. The use of dosimetric instrumentation allows a means for the quantification of the absorbed dose or specific absorption rate (SAR), which is expressed in watts per kilogram. Use of the absorbed dose rate rather than the external exposure (power density) is critical in assessing microwave bioeffects. SAR data provide key information that allow the determination of the precise level at which a biological response occurs in an exposed individual.

Some reactions to microwave/radio-frequency exposure may lead to measurable biological effects that remain within the range of normal (physiological) compensation. Most biological effects occur by thermal energy conversion (heating). Low level exposure (<10 mW/cm^2) may result in transient functional central nervous system changes (Michaelson, 1980).

All behavioral effects studies have shown that megawatt irradiation suppresses the ability to perform a trained task (e.g., a rhesus monkey pushing a lever for food) and that a power-density/dose-rate and duration threshold for achieving the suppression exists (ranging from 5 to 50 mW/cm^2). A projected model from animals shows that the threshold of behavior disruption of a learned task for a human occurs at a power density of approximately 110 mW/cm^2 (Michaelson, 1980).

A useful value to calculate when considering a microwave source is the effective radiated power (ERP), which is given by:

$$ERP = P * G \tag{3.3}$$

where P is the power in milliwatts and G is the gain ratio. The gain ratio is:

$$G = \log^{-1} [G(dB)/10] \tag{3.4}$$

where G(dB) is the gain in decibels. Once the ERP is known, a simple calculation will yield the power density (S) in milliwatts per square centimeter. The power density can be calculated by the following:

$$S = ERP \div (4\pi R^2) \quad (3.5)$$

where R is the distance from the source to the person given in centimeters. This calculation assumes far field conditions and a point source.

Finally, the only proven effects from radio-frequency radiation (RFR) are thermal burns, signs of electric shock or burn, and reasonably prompt cataract formation. The thermal effect has already been discussed, but it is important to note that at frequencies over 10 kHz air may become ionized at approximately 1,000 kV/m; this could result in potentially hazardous electric discharges. Also, electric shock can result from currents induced in conductors within the RFR field. Cataracts and vacuoles have been produced in animal eyes with power densities of 100 mW/cm^2 delivered locally for a period of 15 min. This exposure results in an eye temperature of 41°C or more (Poitrast, 1986).

Effects on the hematopoietic, immune, endocrine, and nervous systems are under continued investigation for RFR effects. Cardiovascular, blood-brain barrier, and behavior effects are also under investigation. Results to date in these areas are inconclusive.

Occupational Limits

The occupational exposure limit at any given time for a radio-frequency electromagnetic (RFEM) field is a SAR of 0.4 W/kg. For humans, the resonant frequency domain is taken to be in the frequency of 30–300 MHz; a power density of 1 mW/cm^2 averaged for 6 min results in the occupational limit. Tables 3-4 and 3-5 further break down the RFEM field limits for all frequencies. At the given frequencies and power densities averaged over a period of 6 min, the yield is the maximum limit for SAR = 0.4 W/kg (NCRP, 1986). Tables 3-4 and 3-5 show the occupational limits for RFEM fields in restricted and nonrestricted areas respectively.

One type of calculation that is useful in determining safe distances from radio-frequency electromagnetic fields is given by the following:

$$d = [PG \div (4\pi P_d)]^{0.5} \quad (3.6)$$

where d is the distance limit in meters, P is the power of the transmitter in watts, G is the gain ratio for the antenna, and P_d is the permissible limit in watts per meter. Note that this equation is simply a variation of Equation (3.5). Equations (3.5) and (3.6) assume a far-field condition. If, however, a far-field condition does not exist, the formula is still correct if the near-field gain beam widths are used. For rotating antennas, use the average power given by the following equation:

$$P = W_b/360 * S \quad (3.7)$$

where W_b is the beam width in degrees and S is the measured or computed power density in watts per meter.

Table 3-4. ANSI Occupational Limits for RFEM Fields in Restricted Areas[a] (Based on NCRP, 1986, and Petersen, 1991)

Frequency Range, f(MHz)	Electric Field Strength, E^2 (V^2/m^2)	Magnetic Field Strength, H^2 (A^2/m^2)	Equivalent Plane Wave Power Density, S (mW/cm^2)
0.3–3	400,000	2.5	100
3–30	$4{,}000 * (900/f^2)$	$0.025 * (900/f^2)$	$900 \div f^2$
30–100	4,000	0.025	1
100–1,000	$4{,}000 * (f/100)$	$0.025 * (f/100)$	$f \div 100$
1,000–300,000	40,000	0.25	10

a. A restricted area has access limited by the licensee for the purpose of protecting individuals against undue risk from exposure to radiation. This area has potential for levels of exposure that are higher than levels that are allowed for the general public.

Table 3-5. ANSI Occupational Limits for RFEM Fields in Nonrestricted Areas[a] (Based on NCRP, 1986, and Petersen, 1991)

Frequency Range, f(MHz)	Electric Field Strength, E^2 (V^2/m^2)	Magnetic Field Strength, H^2 (A^2/m^2)	Equivalent Plane Wave Power Density, S (mW/cm^2)
0.3–3	400,000	2.5	100
3–30	$4{,}000 * (900/f^2)$	$0.025 * (900/f^2)$	$900 \div f^2$
30–300	4,000	0.025	1
300–1,500	$4{,}000 * (f/300)$	$0.025 * (f/300)$	$f \div 300$
1500–300,000	20,000	0.125	5

a. A nonrestricted area is neither limited nor controlled by the licensee. This type of area has no potential for exposure at levels higher than those allowed for the general public.

LASERS

This section of the report includes a basic review of lasers and ultraviolet radiation. The biological effects of laser radiation on the eye and the skin are discussed, as well as the occupation limits based on these biological effects. Finally, several laser protection methods are considered.

Laser Review

A laser is a device that produces a monochromatic beam of light in the ultraviolet, visible, or infrared regions of the electromagnetic spectrum. The waves of this beam are all in phase (i.e. coherent in both space and time). Laser beams can be broken down into four distinct categories based on emission wavelength. Table 3-6 displays this division. Recall that Figure 3-1 shows some common lasers that emit in each distinct region.

Table 3-6. Laser Spectrum Regions

Spectrum Region	Wavelength (nm)
Ultraviolet (UV)	200–400
Visible (light)	400–700
Near-infrared (near-IR)	700–1,400
Far-infrared (far-IR)	$1{,}400–10^6$

Lasers operate in one of three different methods: continuous wave (CW), pulsed, or Q-switched. The optical cavity of the laser system has one end that completely reflects. The other end partially reflects and partially transmits. The operation of the laser depends upon certain characteristics of the optical cavity. Table 3-7 shows some of the principle operating characteristics for typical commercial lasers.

A continuous wave is produced when two conditions are met. First, the partially transmitting end of the optical cavity must allow some of the light energy that strikes it to escape. Second, energy must be pumped into the lasing medium at a rate such that the laser output is maintained constantly. An example of a CW laser is a CO_2 laser.

Pulsed lasers normally deliver output in the form of bursts of light with a duration on the order of about 0.1 to 10 ms. An example of a pulsed laser is the ruby laser.

A specific type of a pulsed laser is the Q-switched laser. A Q-switch is an acousto-optical or electrooptical device within the optical cavity that is analogous to a shutter. Hence, it prevents laser emission until it is opened. Typical pulse durations for Q-switched lasers are on the order of 1ns-100 fs.

Biological Effects

Light, both visible and ultraviolet, is biophysically active. Mechanisms of biological damage from light include both temperature effects and photochemical reactions. The main mechanism of damage depends on the wavelength of the light and on the type of tissue exposed. For lasers, this main mechanism is believed to be due to temperature effects. The critical organs and tissues for this damage are the eye and the skin.

EYE DAMAGE

The eye is normally the most vulnerable organ for laser radiation damage. More specifically, different eye tissues suffer different effects depending upon the wavelength of the laser radiation. The structure of the eye that is damaged depends upon the wave-length of the light and the energy absorption characteristics of the ocular tissues. The retina is sensitive to wavelengths in the range of 400–1400 nm (visible and near-IR band), while the lens and cornea respond to UV-A. The cornea alone is sensitive to far-IR and all UV.

The basic factor in retinal damage is the rate at which heat energy can be dissipated from the irradiated tissue. A temperature increase of several degrees higher than that experienced during fevers is believed to be capable of producing permanent damage to the retina. Table 3-8 shows the threshold values for damage to the retina from visible light. It is reasonable to assume there is little or no difference over the entire visible spectrum, so no values are listed for specific wavelengths (Cember, 1987). On the basis of these thresholds, typical mission failure for a nanosecond pulsed laser is usually taken as 3.9 mJ/cm^2 for a large hemorrhagic lesion. This value corresponds to 1.5 mJ over a 7 mm pupil (Rodgers, 1994).

Pigments and other tissue constituents determine the absorption characteristics of eye tissue. The cornea and lens will absorb most of the radiation in the ultraviolet region with a wavelength of less than 400 nm. Some of the incident radiation in the 315–340 nm region will be transmitted and absorbed by the retina. Radiation in the range of 400–1400 nm is almost completely transmitted through the cornea and lens. The retina and choroid absorb most of the radiation in this range, with the longer wavelengths penetrating to deeper tissues. Radiations in the far-infrared region, 1400–10^6 nm, are almost completely

absorbed by the cornea. From 1200–1400 nm, radiation is absorbed by the retina, cornea, and lens (Rademacher, 1992). For these different wavelengths, Table 3-9 shows exposure levels required for 50% probability of damage for minimal visible lesion (MVL) and vitreal hemorrhage (VH).

Table 3-7. Principal Characteristics of Common Lasers (Green, 1988)

Waveband	Wavelength	Lasing Medium	Perceived Hue	Typical
UV	325	Helium-Cadmium	N/A	CW
UV	337	Nitrogen	N/A	Pulsed
UV	351	Argon	N/A	CW
Visible	441.6	Helium-Cadmium	Reddish-Blue	CW
Visible	458	Argon	Blue	CW
Visible	468	Krypton	Blue	CW
Visible	488	Argon	Blue-Green	CW
Visible	511	Copper Vapor	Green	Pulsed
Visible	514.5	Argon	Green	CW
Visible	530	Doubled Nd:Glass	Yellowish-Green	Pulsed
Visible	532	Doubled Nd:YAG	Yellowish-Green	Pulsed
Visible	568	Krypton	Yellow	CW
Visible	632.8	Helium-Neon	Red	CW
Visible	647	Krypton	Red	CW
Visible	694.3	Ruby	Red	Pulsed
Near-IR	755	Alexandrite	N/A	Pulsed
Near-IR	905	Gallium-Arsenide	N/A	Pulsed
Near-IR	1,060	Nd:Glass	N/A	Pulsed
Near-IR	1,064	Nd:-YAG	N/A	Pulsed
Far-IR	10,600	Carbon Dioxide	N/A	CW, Pulsed

Table 3-8. Thresholds for Retinal Damage (Cember, 1987)

Laser Type	Wavelength	Pulse	Level
Continuous wave	visible light	N/A	6 W/cm^2
Normal pulse	694 nm	200 μs	0.85 J/cm^2
Q-switched pulse	694 nm	30 ns	0.07 J/cm^2

Table 3-9. Exposure Levels Required for MVL and VH (Meyers, 1990)

Wavelength (μm)	Exposure Required for MVL (μJ)	Exposure Required for VH (μJ)
0.488	3	157
0.532	3	155
0.694	15	240
1.06	220	2,300

Several nondamaging effects may occur after laser exposure. These effects are glare, flashblindness, and afterimage.

Exposure to continuous wave or pulsed lasers (where the pulse repetition frequency is less than 100 Hz) can produce glare similar to that which one experiences when viewing bright light sources like the sun or the headlight of an automobile. The glare effects are more pronounced when the laser is near objects being viewed. The luminance, L_S, required to produce glare can be determined from the following equation:

$$L_s^{\,3} (816 \times L_o/\Theta) \qquad (3.8)$$

where Θ is the angular subtense of the source in radians and L_o is the background luminance (Rademacher, 1992).

Experiments conducted by the Naval Aerospace Medical Research Laboratory (NAMRL) show that delay-of-glare-onset (DGLO) affects both speed and accuracy of target location performance. Visual decrements were noticed even when exposures were hundreds of times lower than the maximum permissible exposure (MPE) for low-level argon laser-induced glare. The NAMRL recommended that eye protection should be required to prevent mission disruption at laser intensities that are not harmful to the eye (Reddix, 1992).

Flashblindness effects can last a few seconds to minutes, depending on the intensity of the light source, ambient lighting, and the brightness of the object being viewed. The magnitude of the impairment is largely a function of the size and location of the area of the eye affected (Rademacher, 1992).

Afterimage is the perception of light, dark, or colored spots after exposure to a bright light. This effect may persist for many days but it is unlikely to cause visual decrement.

SKIN DAMAGE

When the skin receives an acute exposure from a laser, the skin may receive burns that are much like ordinary thermal or solar burns. The exposed skin undergoes coagulation necrosis of a degree that is directly proportional to the amount of energy absorbed by the skin. The temperature rises only in the local tissue area, since skin has poor thermal conductivity properties. Such a temperature rise leads to the denaturation of tissue proteins. If a great amount of energy is absorbed, the water in the skin tissue is vaporized. After this, the tissue may be heated to incandescence and may be carbonized.

Injury to skin from laser light depends on two different factors. First, the degree of damage to the skin from lasers increases as the degree of pigmentation increases. Second, damage to the skin depends on the wavelength of the laser and the length of the exposure time. Table 3-10 lists the threshold doses to the surface of the forearm of a Caucasian adult for several different conditions of exposure. These thresholds are called minimal reactive doses (MRD). At the MRD level and below, there will be no damage to the skin.

Occupational Limits

In the United States, laser safety regulations are declared by two agencies: the Department of Health and Human Services through the Bureau of Radiobiological Health and the Department of Labor through the Occupational Safety and Health Administration. Table 3-11 displays eye and skin effects for various spectral exposures that these agencies use to form occupational limits. On the basis of the eye effects in Table 3-11, Table 3-12 shows the occupation limits for lasers as regulated by the Occupational Safety and Health

Administration (OSHA). Tables 3-13 through 3-20 show maximum permissible exposures (MPE) for direct ocular viewing, diffuse reflector viewing, and skin exposure.

Table 3-10. Skin Damage Thresholds (Cember, 1987)

Laser	Wavelength (nm)	Exposure Time	Area (cm^2)	MRD (J/cm^2)
Ruby, normal pulse	694	0.2 ms	$2.4–0.4 \times 10^{-3}$	14–20
Argon	500	6 s	95×10^{-3}	13–17
CO_2	1060	4–6 s	1	4–6
Ruby, Q-switched	694	10–12 ns	0.33–1.0	0.5–1.5

Table 3-11. Biological Effects of the Optical Radiation Spectrum (Schleien, 1992)

Spectral Division	Spectral Range (nm)	Eye Effects	Skin Effects
UV-C	100–280	Photokeratitis	Erythema, accelerated aging, cancers, pigment darkening
UV-B	208–315	Cataract	
UV-A	315–400		
Visible	400–770	Lens yellowing, photochemical and thermal retinal injuries, retinal lesions, thermal cataract, aqueous flare, corneal burn	Photosensitivity, burns
IR-A	770–1400		
IR-B	1400–3000		
IR-C	$3000–10^6$		

Table 3-12. OSHA Maximum Exposure-Level Limits for Light Intensities for Employees

Viewing Orientation	Light Intensity
Direct staring	$1 mW/cm^2$
Incidental observation	$1 mW/cm^2$
Diffuse reflected light	$2.5 W/cm^2$

Table 3-13. MPE for Direct Ocular Exposure, Intrabeam Viewing, to a UV Laser Beam or for Viewing a Diffuse Reflector of a UV Laser Beam[a] (Rademacher, 1992)

Wavelength, λ (nm)	Exposure Duration, t(s)	MPE (J/cm^2)
200–302	10^{-9}–3×10	3×10^{-3}
303	10^{-9}–3×10^{4}	4×10^{-3}
304	10^{-9}–3×10^{4}	6×10^{-3}
305	10^{-9}–3×10^{4}	1.0×10^{-2}
306	10^{-9}–3×10^{4}	1.6×10^{-2}
307	10^{-9}–3×10^{4}	2.5×10^{-2}
308	10^{-9}–3×10^{4}	4.0×10^{-2}
309	10^{-9}–3×10^{4}	6.3×10^{-2}
310	10^{-9}–3×10^{4}	1.0×10^{-1}
311	10^{-9}–3×10^{4}	1.6×10^{-1}
312	10^{-9}–3×10^{4}	2.5×10^{-1}
313	10^{-9}–3×10^{4}	4.0×10^{-1}
314	10^{-9}–3×10^{4}	6.3×10^{-1}
315–400	10^{-9}–10	$0.56 * t^{0.25}$
315–400	10–3×10^{4}	1

a. MPE is either the tabulated value or $0.56 * t^{0.25}$ (where t is the exposure duration in seconds), whichever value is lower

For safety purposes, lasers have been segregated into four classes based upon their strength and biological effects. Class I lasers produce levels of radiation that do not cause

biological damage. They emit less than 0.39 μW of continuous output. Class II lasers produce radiation that can cause eye damage after direct, long term exposure and emit less than 1 mW of continuous output. Class III lasers produce radiation powerful enough to injure human tissue with one short exposure to the direct beam or its direct reflections off a shiny surface. They emit less than 500 mW of continuous output. Finally, Class IV lasers produce radiation so powerful that it can cause injury with a direct or reflected exposure, even if the beam is scattered or diffused by a rough surface or smoke screens. They emit more than 500 mW of continuous output (Schleien, 1992).

Table 3-14. MPE for Direct Ocular Exposure, Intrabeam Viewing, to Visible and Near-Infrared Laser Beam[a] (Rademacher, 1992)

Wavelength, λ(nm)	Exposure Duration, t(s)	MPE (J/cm^2)
400–700	10^{-9}–1.8×10^{-5}	5×10^{-7}
400–700	1.8×10^{-5}–10	$1.8 * t^{0.75} * 10^{-3}$
400–550	10–10^4	10×10^{-3}
550–700	10–T_1	$1.8 * t^{0.75} * 10^{-3}$
550–700	T_1–10^4	$10C_B\times 10^{-3}$
400–700	10^4–3×10^4	$C_B\times 10^{-6}$ (W/cm^2)
700–1050	10^{-9}–1.8×10^{-5}	$5C_A\times 10^{-7}$
700–1050	1.8×10^{-5}–10^3	$1.8 * C_A^{0.75} * 10^{-3}$
1051–1400	10^{-9}–5×10^{-5}	5×10^{-6}
1051–1400	5×10^{-5}–10^3	$9 * t^{0.75} * 10^{-3}$
700–1400	10^3–3×10^4	$320C_A\times 10^{-6}$ (W/cm^2)

a. $T_1 = 10\times 10^{0.02\,(\lambda - 550)}$ for λ = 550–700 nm

$C_A = 1$ for λ = 400 – 700 nm $C_A = 10^{0.002(\lambda - 700)}$ for λ = 700–1050 nm

$C_A = 5$ for λ = 1050–1400 nm $C_B = 1$ for λ = 400–550 nm

$CB = 10\times 10^{0.015(\lambda - 550)}$ for λ = 550–700 nm

Table 3-15. MPE for Viewing a Diffuse Reflector of a Visible Laser Beam[a] (Rademacher, 1992)

Wavelength, λ (nm)	Exposure Duration, t(s)	MPE ($J/sr \cdot cm^2$)
400–700	10^{-9}–10	$10 * t^{0.333}$
400–550	10–10^4	21
550–700	10–T_1	$3.8 * t^{0.75}$
550–700	T_1–10^4	$21C_B$
400–700	10^4–3×10^4	$2.1\ C_B \times 10^{-3}$ ($W/sr \cdot cm^2$)

a. $T_1 = 10 \times 10^{0.02(\lambda - 550)}$ for λ = 550–700 nm
$C_B = 1$ for λ = 400–550 nm
$CB = 10 \times 10^{0.015(\lambda - 550)}$ for λ = 550–700 nm

Table 3-16. MPE for Viewing a Diffuse Reflector of a Near-Infrared Laser Beam[a] (Rademacher, 1992)

Wavelength, λ (nm)	Exposure Duration, t(s)	MPE ($J/sr \cdot cm^2$)
700–1400	10^{-9}–10	$10C_A * t^{0.333}$
700–1400	10–10^3	$3.83C_A * t^{0.75}$
700–1400	10^3–3×10^4	$0.64C_A$ ($W/sr \cdot cm^2$)

a. $C_A = 1$ for λ = 400–700 nm
$C_A = 10^{0.002(\lambda - 700)}$ for λ = 700–1050 nm
$C_A = 5$ for λ = 1050–1400 nm

Table 3-17. MPE for Direct Ocular Exposure, Intrabeam Viewing, to a Far-IR Laser Beam, or for Viewing a Diffuse Reflector of a Far-IR Laser Beam (Rademacher, 1992)

Wavelength, λ(nm)	Exposure Duration, t(s)	MPE (J/cm^2)
1400–10^6	10^{-9}–10^{-7}	10^{-2}
1400–10^6	10^{-7}–10	$0.56 * t^{0.25}$
1400–10^6	10–3×10^4	$0.1 * t$
1540 only	10^{-9}–10^{-6}	1.0

Table 3-18. MPE for Skin Exposure to a UV Laser Beam

Wavelength, λ(nm)	Exposure Duration, t(s)	MPE (J/cm^2)
200-302	10^{-9}–3×10	3×10^{-3}
303	10^{-9}–3×10^4	4×10^{-3}
304	10^{-9}–3×10^4	6×10^{-3}
305	10^{-9}–3×10^4	1.0×10^{-2}
306	10^{-9}–3×10^4	1.6×10^{-2}
307	10^{-9}–3×10^4	2.5×10^{-2}
308	10^{-9}–3×10^4	4.0×10^{-2}
309	10^{-9}–3×10^4	6.3×10^{-2}
310	10^{-9}–3×10^4	1.0×10^{-1}
311	10^{-9}–3×10^4	1.6×10^{-1}
312	10^{-9}–3×10^4	2.5×10^{-1}
313	10^{-9}–3×10^4	4.0×10^{-1}
314	10^{-9}–3×10^4	6.3×10^{-1}
315–400	10^{-9}–3×10	$0.56 * t^{0.25}$
315–400	10–10^3	1
315–400	10–3×10^4	$10^{-3} * t$

Table 3-19. MPE for Skin Exposure to Visible and Near-Infrared Laser Beams[a] (Rademacher, 1992)

Wavelength, λ(nm)	Exposure Duration, t(s)	MPE (J/cm^2)
400–1400	10^{-9}–10^{-7}	$2C_A \times 10^{-2}$
400–1400	10^{-7}–10	$1.1C_A t^{0.25}$
400–1400	10–3×10^4	$0.2C_A$ (W/cm^2)

a. $C_A = 1$ for $\lambda = 400$–700 nm
$C_A = 10^{0.002(\lambda - 700)}$ for $\lambda = 700$–1050 nm
$C_A = 5$ for $\lambda = 1050$–1400 nm

Table 3-20. MPE for Skin Exposure to Far-Infrared Laser Beams (Rademacher, 1992)

Wavelength, λ(nm)	Exposure Duration, t(s)	MPE (J/cm^2)
1400–10^6	10^{-9}–10^{-7}	10^{-2}
1400–10^6	10^{-7}–10	$0.56 * t^{0.25}$
1400–10^6	>10	$0.1 * t$
1540 only	10^{-9}–10^{-6}	1.0

Useful Calculations

Once the MPE is known, it is also useful to express it in terms of the average irradiance (E) given in watts per centimeter squared:

$$E = H/T \tag{3.9}$$

where H is the radiant exposure, or MPE, in joules per centimeter squared, and T is the total exposure duration of a train of pulses. Finally, expressed in terms of the radiant exposure for a single pulse, the MPE is:

$$\text{MPE (single pulse)} = H/n \tag{3.10}$$

where n is the multiple of the PRF and the total exposure duration.

Another calculation that is especially helpful when considering laser effects is one that determines the fluence at a given distance. The following equation is only a first-order analysis; it does, however, permit for atmospheric effects, canopy and visor attenuation, and repetitively pulsed lasers:

$$H = \{4Q[(PRF)(t_{exp})]^{0.25} * (T_c T_a 10^{-OD})\} \div [\pi (a^2 + s^{2\phi})] \tag{3.11}$$

where Q is the energy per pulse in joules, PRF is the pulse repetition rate in hertz, t_{exp} is the exposure time in seconds, and T_c and T_a are the fraction transmissions by the canopy and atmosphere respectively. The term $[(PRF)(t_{exp})]$ is simply the total number of pulses, n. The visor attenuation is modeled by the optical density (OD). The term 'a' is the width of the beam as it leaves the laser source. The term 's' is the slant range in centimeters given by:

$$s = (r^2 + h^2)^{0.5} \tag{3.12}$$

where r is the range and h is the altitude of the target. Finally, $\phi$is the beam divergence given in radians.

One factor the analyst may require is one that represents the attenuation coefficient that affects the transmission capability for typical battlefield obscurants. Table 3-20 summarizes several coefficients for such obscurants. The transmission factor for such situations is given by:

$$T = e^{-\mu\rho x} \tag{3.13}$$

where μ is the attenuation coefficient as given in Table 3-21, ρ is the concentration in grams per meter cubed, and x is the path length in meters.

Table 3-21. Obscurant Attenuation Coefficients (m^2/g) (IRIA, 1980)

Obscurant	Wavelength (μm)			
	0.55	1.06	10.6	11.15
Phosphorus	4.49	1.55	0.341	0.208
Hexachloroethane	4.70	2.06	0.056	0.075
Fog oil	7.37	3.53	0.016	0.024

Protection Against Laser Weapons

Several different methods have been used to protect sensors or eyes from lasers. The beam may be blocked by an attenuating filter placed in front of the sensor or eye. These filters must be effective against specific laser wavelengths and at the same time allow sufficient amounts of other wavelengths to be transmitted for target detection or general surveillance. Another approach may be to block the beam by using indirect viewing methods through an electrooptical system such as a thermal sight or a low-light television device. Other methods of laser protection include veiling smoke, rapidly closing and opening shutters, and the black eye patch (Anderberg, 1993).

When discussing the degree of protection from a filter, the term *optical density* is used. Optical density is a measure of the attenuation of the light beam due to a transmitting medium and is given by the following:

$$OD = \log (I_O/I) \tag{3.14}$$

where OD is the optical density, I_O is the power of the incident beam and I is the power of the transmitted beam. For laser filters, researchers look for optical densities as high as 18. When choosing protective filters, the luminous transmission must also be considered. The optimum protective filter is one that provides maximum attenuation of the laser light while transmitting the maximum amount of ambient light. Luminous transmission is given as the percentage of transmission of light from a source. Eye protection on the battlefield should typically have an overall transmission of 80% visible light through the filter (Anderberg, 1993).

The most commonly used filter for military applications is the absorption filter, which can be composed of either glass or plastic. Absorbing dyes can also be used in absorption filters; these dyes can have optical density up to the range of 16 to 20. Dye filters are simple and inexpensive; however, their optical density can be lowered by aging, oxidation, or exposure to sunlight (Anderberg, 1993).

Instead of plastic absorption filters, colored glass can be used. Such filters are more stable; however, in the near infrared region, only a few different wavelength absorption curves are available.

Insulating or dielectric coatings are another filter type that were developed to suppress reflections from lenses. The modern dielectric interference filter selectively reflects different wavelengths. Since such filters consist of alternating layers of different dielectric materials, a sharp spectral image can be obtained (i.e. a specific wavelength is reflected while other

nearby wavelengths in the visible part of the spectrum are transmitted). The disadvantage of these filters is that the light reflected changes as the viewing angle changes (Anderberg, 1993).

Finally, a hologram can be made of one plate and it will respond to light just as the multilayered dielectrics do. Holographic filters have the same advantages and disadvantages as the dielectric filters. Another advantage the holographic filter has is that it can scatter or bend laser light in a controllable way (Anderberg, 1993).

Crews inside tanks and other armored fighting vehicles (AFV) can be protected by filters and coatings applied to sights and vision blocks. If such protection is sufficient to block any laser beam from entering the vehicle, then the crew does not require individual eye protection. For those cases in which crews will be exposed, the members can be equipped with laser protective visors. Wrap-around laser protective visors that can be mounted on the helmet are currently being developed; however, such protection would not be sufficient against low-energy laser weapons that can use varying wavelengths (Anderberg, 1993).

In certain scenarios, other protective methods may be more applicable or can be used in addition to filters. Another protective method is to use some form of indirect viewing, such as a TV system, a thermal imager, or a light intensifier. A disadvantage of using this method is that there are times when one must be able to view the battlefield with the naked eye. Smoke can be used not only to make target acquisition difficult for the enemy, but if it is dense enough, it can diffuse and absorb a laser beam. Obviously, because smoke must be able to cover an extensive area densely and maintain that density, it has a great deal of limitations. For infantry or combat soldiers who fight in an area where lasers are a threat, if no other means are available, a black patch can be worn over one of the eyes. This method also has obvious disadvantages. The soldiers lose their depth perception and it possible that one eye may be lost (Anderberg, 1993).

4. SCENARIOS

This chapter is designed to show the reader how to use Chapters 2 and 3 to predict how humans would perform after exposure to nuclear and advanced technology weapons. Each scenario presents a typical environment and then steps through a solution by referring to equations and tables in Chapters 2 and 3. Some of the physical characteristics (e.g., wavelength) discussed in these scenarios are representative of actual systems. Others are simply general estimates.

IONIZING RADIATION

Hard Mobile Launcher

This scenario involves driving a hard mobile launcher (HML) from an alert area to a place where the missile could be launched. The HML consists of two parts, the tractor and the trailer. The tractor carries a two-person crew and pulls the trailer. The trailer contains an intercontinental ballistic missile (ICBM) and the necessary support equipment to launch the missile on command. The crew would drive the HML from the alert area to a predetermined location and detach the missile trailer and leave it. Once the crew had left the missile, their mission would be complete.

The crew could be exposed to the effects of nuclear weapons from nearby detonations. The scenario assumes a 50/50 mix of gamma and neutron radiation. The crew would be protected from blast and thermal radiation by hardening the tractor to blast, blocking all windows, and using TV cameras while driving.

Table 2-4 shows that if the crew absorbed 600 cGy of prompt radiation, they would begin vomiting and retching within 0.5–1 h. Hence, a 20-min mission probably could be completed before the prodromal symptoms began. If the crew received a dose of 400 scGy, they probably could continue driving a vehicle for 1 h before the onset of vomiting and nausea. A maximum dose of 200 cGy would allow the crew to drive for 2 h before the onset of prodromal symptoms. Table 4-1 summarizes these data.

If the crew were not protected against blast and thermal effects, what overpressure and thermal levels could they withstand? Table 2-8 shows the limiting health effect from blast overpressure is eardrum rupture, which occurs at 15 psi for 50% of the population over 20 yr of age. The threshold for eardrum rupture is 5 psi, which should be regarded as the limiting value for blast effects when considering mission failure. Second degree burns are the limiting factor for thermal effects.

Table 4-1. Maximum Prompt Dose for Timed Vehicle Operation

Time Required to Complete Mission	Maximum Dose if Task Is to Be Completed (cGy)
20 min	600
1 h	400
2 h	200

Strategic Aircraft

The second scenario involves the use of a strategic bomber aircraft (A/C) to bomb a target in Europe. The mission originates from the CONUS. The pilot would fly at a high altitude until penetrating the enemy radar, then fly at an altitude of several hundred feet until reaching the target. Once the target was bombed, the mission would be complete.

The flight is estimated to take 12 h. Once the bomber entered the enemy airspace, the crew would be exposed to the effects of nuclear weapons from nearby detonations. The scenario assumes a 50/50 mix of gamma and neutron radiation. At issue is the question of how much prompt ionizing radiation the pilot could absorb and still complete the mission.

Table 2-4 shows that a pilot who received 130 cGy of prompt radiation probably would be physically capable of completing a 12-h mission, although the individual most likely would be nauseated and perhaps vomit. Notice that the limiting value for a pilot is more strict than for the operator of a hard ground mobile launcher; this difference is due to the fact that a pilot must be more alert and in a better state of health than a ground vehicle operator.

Mobile Ground Communication Systems

This scenario shows how to use the information on the health effects of radiation to help set radiation levels for mobile ground systems. Mobile communication systems are used to provide survivable communications after a nuclear attack. Since the systems are mobile, they cannot be directly attacked. Therefore, the only nuclear environments that affect them are those that cover a wide area, such as fallout.

Fallout produces two primary kinds of radiation: beta and gamma. As mentioned in the section on fallout radiation, beta radiation has a short range. People can be shielded from

beta radiation by protective clothing and respirators, and equipment can be shielded by air filters. The primary hazard from fallout then becomes the gamma radiation. Tables 2-5 and 2-6 give the human effects of exposure to gamma radiation. Before we can use the tables, we must examine the operations concept for the mobile ground system.

For this example, let's assume that the system has to operate for at least 6 mo after a general nuclear exchange. The system is mobile and can be moved to reduce its fallout exposure. Further, let's assume that the shelter housing the communication equipment is made of thin sheets of metal over plywood and two-by-fours. This shelter provides essentially no protection against gamma radiation. Finally, let's assume that two operations concepts for the system are being considered. In the first concept, the mobile system would have a single crew. This crew would be deployed with the system before the start of the nuclear exchange. In the second concept, a replacement crew would be housed in a fallout shelter until the crew was needed to operate the system.

In the first operations concept, a single crew would have to operate the mobile system for 6 mo. Fallout levels high enough for people to begin dying would jeopardize the mission. Table 2-5 shows that 10% of exposed people would die at a tissue dose of 110 cGy; therefore, the radiation-exposure level for the system should be set at about 110 cGy. Table 2-6 shows that there is no need to revise the dose upward to account for the effects of the fallout dose being delivered over time since most of the fallout radiation (89%) is received within the first week after the nuclear detonation.

In the second operations concept, the mission could still be successful if the members of the first crew received a high dose and were replaced. The question then becomes how high a dose the crew could receive and still function well enough to turn the system over to the replacement crew. Table 2-5 shows that about half of the crew would die from a dose of about 345 cGy. Also, about half of the crew would suffer from diarrhea and hemorrhaging at this dose level, and well over half would suffer from nausea, fatigue, and vomiting. Therefore, a dose of about 350 cGy is probably the maximum dose that the first crew could receive and still function well enough to turn the system over to the replacement crew. The replacement crew could then receive a dose of about 110 cGy and continue to operate the system to finish the 6 mo mission. The total dose for the system would be about 450 cGy.

Notice that the discussion above shows how to use the survival of the crew in a fallout environment to balance the hardness requirements of the equipment in the mobile ground system. This is normally a logical way to estimate the hardness requirements for manned systems. However, this analysis does not show whether the system would be able to accomplish its mission after a nuclear attack. We would have to identify the deployment areas for the mobile system and estimate the levels of fallout radiation that those areas probably would receive before we could estimate the fallout levels for the system.

HIGH-POWERED RADAR

AN/APQ-120 Radar

The third scenario involves a multimode AN/APQ-120 radar system on an F-4E aircraft. The system has one transmitter with a continuous wave (CW) output and another with a pulsed output. The pulsed transmitter has two discriminate pulse-width/pulse-repetition-frequency (PW/PRF) combination modes. The system not only is capable of scanning operator-variable sector sizes, but also can operate in a fixed-beam mode if the antenna hydraulics are shut off or if the antenna is mechanically pinned (Rademacher, 1989).

The operating parameter of the AN/APQ-120 for CW is 120.02–10.25 GHz with a power of 200 W. During the pulsed mode, the frequency is 8.7–9.4 GHz with a power of 165 kW (maximum peak) and 135 kW (minimum peak). The PRFs are 300 pps and 1060 pps.

In 1989 there was an instance of accidental human exposure to the main beam of the AN/APQ-120 radar. Incorrectly assuming the dummy load was engaged, an individual performed routine testing in the main beam of the radar at a distance of 3 ft from the antenna. This individual was exposed to the main beam for approximately 3 min with the CW transmitter and for 1 min with both transmitters. The antenna was in a fixed-beam mode (Rademacher, 1989).

To calculate the individual's exposure, the power density was measured with the radar in the CW and pulsed modes with the longest duty cycles. This produced a power density of 220 mW/cm^2 and 125 mW/cm^2 for each mode respectively. The exposure was averaged over a 6 min period. Given:

3 min at 220 mW/cm^2 and
1 min at 125 mW/cm^2 and 220 mW/cm^2, simultaneously

simple averaging over 6 min yields:

$$[(4 \text{ min} * 220 \text{ mW/cm}^2) + (1 \text{ min} * 125 \text{ mW/cm}^2)] \div 6 \text{ min} = 167.5 \text{ mW/cm}^2 \quad (4.1)$$

This estimated exposure exceeds the limit of 10 mW/cm^2. The only effect the individual experienced at the time of overexposure was a warming sensation on the back of his neck (Rademacher, 1989).

Large Phased-Array Radar (LPAR)

In this scenario, a large phased-array radar (LPAR) on an aircraft is assumed to possess the following specifications:

f = 16 GHz
dish diameter = 0.5 m
gain = 35 dB
P = 300 kW

Under these conditions, what power density would a person be exposed to at 100 m from the source? For reasons of simplification, assume far field conditions and a point source.

To calculated the effective radiated power (ERP), one must first determine the gain ratio. Using Equation (3.4), the gain ratio is:

$$G = \log^{-1}[\, G(dB)/10] \qquad (3.4)$$

$$G = \log^{-1}[35/10] = 3{,}162 \qquad (4.2)$$

Using Equation (3.3), the effective radiated power is:

$$ERP = P * G \qquad (3.3)$$

$$ERP = 100\ kW * 3{,}162 = 3.162 \times 10^5\ kW \qquad (4.3)$$

Finally, with the aid of Equation (3.5), the power density (S) is:

$$S = ERP \div [4^1R^2] \qquad (3.5)$$

$$S = 3.16 \times 10^5\ kW \div [4^1(100\ m)^2] = 2.5\ kW/m^2 = 250\ mW/cm^2 \qquad (4.4)$$

Table 3-4 shows an ANSI occupational limit for RFEM fields in restricted areas of 10 mW/cm^2 for a frequency of 16 GHz. It is possible that disruption of a learned task could occur at this power density.

Tactical Aircraft

This scenario considers the effect of a ground-based generic laser on a pilot behind the canopy of a tactical aircraft. The laser is assumed to have an output of 100 mJ, a wavelength of 10.064 m, and a narrow beam divergence of 100 μrad.

If the pilot did not have a protective visor (i.e., OD = 0), what exposure would he receive at an altitude of 1,000 ft and a distance of 0.5 mi from the ground-based laser source? Assume the following conditions (Rodgers, 1994):

PRF = 10 Hz
Exposure period = 10 s
Canopy transmission = 80%
Atmospheric transmission = 92%
Output diameter = 2 cm

The problem can be solved using a simple approach for a first order analysis of laser effects. Recall Equation (3.11):

$$H = \{4Q[(PRF)(t_{exp})]^{0.25} * (T_c T_a 10^{-OD})\} \div [(a^2 + s^2\phi^2)] \qquad (3.11)$$

The first step in solving Equation (3.11) is to solve for the slant range, s. Recall Equation (3.12):

$$s = (r^2 + h^2)^{0.5} \qquad (3.12)$$

Substitute the given values:

$$s = (2640^2 + 1000^2)^{0.5} \text{ ft} = 2823 \text{ ft} = 8.605 \times 10^4 \text{ cm} \qquad (4.5)$$

Now substitute the given values into Equation (3.11):

$$H = \{4(0.1)[(10)(10)]^{0.25} * (0.8)(0.92)(1)\} \div \{\pi[(2)^2 + (8.605 \times 10^4)^2(0.1 \times 10^{-3})^2]\}$$
$$= 3.80 \times 10^{-3} \text{ J/cm}^2 \qquad (4.6)$$

Recall from the data on the biological effects of lasers in Chapter 3 that the typical mission failure for a nanosecond pulsed laser can be taken as 3.9 mJ/cm^2 for a large hemorrhagic lesion. This value corresponds to 1.5 mJ over a 7 mm pupil (Rodgers, 1994). The calculated value in this scenario is close enough to consider mission failure.

What if the pilot were wearing laser eye protection with the usual optical density of 4? Simply adding the optical density factor to Equation (3.11) yields:

$$H = (10^{-4}) \times 3.80 \times 10^{-3} \text{ J/cm}^2 = 3.80 \times 10^{-7} \text{ J/cm}^2 \qquad (4.7)$$

which would fully protect the pilot at all ranges from this laser.

5. SUMMARY AND CONCLUSIONS

This report provides a review of the fundamentals of radiation biophysics and human response to ionizing and non-ionizing radiation. It also provides a background review of nuclear weapons and ATWs. Finally, the report gives examples of how to determine mission survivability in various scenarios. Some of the most useful material for the survivability analyst is contained in the tables.

The review of the biological effects of ionizing radiation focuses on the acute radiation syndrome (ARS). Table 2-4 shows the time until the onset of and the probability of occurrence of prodromal symptoms. This table enables the analyst to determine whether or not a mission is likely to be completed based upon the prompt dose received. Table 2-6, which shows the lethal doses in 60 d for various percentages of the population, enables the analyst to determine mission capability. The most significant figure in this table is the LD_{50} value of 345 cGy. Table 2-7 in the discussion of treatment displays various decontam-ination agents for specific isotopes. The section on nuclear weapons has two tables on human responses to blast effects, Tables 2-8 and 2-9.

The chapter on ATWs does not give as much detail on the effects of human exposure to radiation as the chapter on nuclear weapons. Research has yet to yield data on specific human responses to non-ionizing radiation. Until these data are available, the systems survivability analyst should contact the non-ionizing radiation protection division at Armstrong Laboratory (AL/OER), Brooks AFB, TX. The microwave and laser sections of this chapter do, however, contain the recommend occupational exposure limits, as shown in Tables 3-4, 3-5, and 3-12 through 3-20. These exposure limits give the analyst a rough estimate of what mission-limiting exposures are likely to be.

Finally, the scenarios listed in this report are presented in a manner that shows the systems survivability analyst how to step through a scenario by using information from Chapters 2 and 3. Some of the scenarios are based upon specific systems, while others are based upon generic conditions.

In conclusion, this report provides guidance to system survivability analysts by outlining how human survivability relates to nuclear weapon and ATW effects. With the assistance of this document, the analyst can make quick order-of-magnitude estimates of the hardness requirements for manned systems based on human response to nuclear weapons and ATWs.

USEFUL CONVERSIONS

Conversion Between Irradiance Units

		W/m^2	mW/cm^2	W/cm^2
1 W/m^2	=	1	0.1	0.0001
1 mW/cm^2	=	10	1	0.001
1 W/cm^2	=	10^4	10^3	1
1 $erg/(cm^2 \cdot s)$	=	10^{-3}	10^{-4}	10^{-7}
1 $erg/(m^2 \cdot s)$	=	10^{-7}	10^{-8}	10^{-11}

Conversion Between Radiation Units

To convert from	to	Multiply by
curie	becquerel	3.7×10^{10}
rad	gray	1×10^{-2}
rem	sievert	1×10^{-2}
roentgen	Coulomb/kilogram	2.58×10^{-4}

ACRONYMS AND ABBREVIATIONS

A	Ampere
A/C	Aircraft
AF	Air Force [United States]
AFB	Air Force base
AFV	Armored fighting vehicle
ARS	Acute radiation syndrome
ATW	Advanced technology weapon
C	Centigrade
cGy	Centigray
cm	Centimeter
CNS	Central nervous system
CONUS	Continental United States
CW	Continuous wave
d	Day
D	Absorbed dose
dB	Decibel
DGLO	Delay-of-glare-onset
DNA	Defense Nuclear Agency
D_0	Mean lethal dose
DTPA	Diethylenetriaminepentaacetic acid
E	Electric field strength
EDTA	Ethylenediaminetetraacetic acid
EM	Electromagnetic
EMF	Electromagnetic field
ERP	Effective radiated power
f	Frequency
ft	Feet
G	Gain
GHz	Gigahertz

GI	Gastrointestinal
Gy	Gray
h	Hour
H	Magnetic field strength
HEL	High-energy laser
HML	Hard mobile launcher
HPM	High-powered microwave
Hz	Hertz
IAEA	International Atomic Energy Agency
ICBM	Intercontinental ballistic missile
IR	Infrared
kg	Kilogram
kHz	Kilohertz
Laser	Light amplification by stimulated emission of radiation
LD_{50}	Lethal dose for 50% of the population
LEL	Low-energy laser
L_o	Background luminance
LPAR	Large phased-array radar
L_s	Luminance
m	Meter
MeV	Megaelectronvolt
MHz	Megahertz
mi	Mile
min	Minute
mJ	Millijoule
mm	Millimeter
mo	Month
MPE	Maximum permissible exposure
MRD	Minimal reactive dose
ms	Millisecond
MT	Megaton

µm	Micrometer
µrad	Microrad
µs	Microsecond
MVL	Minimum visible lesion
mW	Milliwatt
MW	Megawatt
MW	Microwave
MW/RF	Microwave/radio frequency
NAMRL	Naval Aerospace Medical Research Lab
NCRP	National Council on Radiation Protection and Measurements
nm	Nanometer
OD	Optical density
OSHA	Occupational Safety and Health Administration
P	Power
pps	Pulses per second
PRF	Pulse repetition frequency
psi	Pounds per square inch
PW	Pulse width
QF	Quality factor
R	Roentgen
RF	Radio frequency
RFEM	Radio-frequency electromagnetic field
RFR	Radio-frequency radiation
s	Second
S	Power density
SAR	Specific absorption rate
sr	Steradian
Sv	Sievert
USANCA	United States Army Nuclear and Chemical Agency
UV	Ultraviolet
V	Volt
VH	Vitreal hemorrhage

W	Watt
wk	Week
yr	Years

GLOSSARY

absorbed dose (*see* dose, absorbed)

acute exposure. Irradiation in which the time of exposure does not extend beyond several hours.

acute radiation dose (*see* dose, acute radiation)

acute radiation stomatitis. Inflammation of the mucous membrane of the mouth.

acute radiation syndrome (ARS). The complex of symptoms characterizing the disease known as radiation injury, resulting from excessive exposure of the whole body (or a large part) to ionizing radiation. The earliest of these symptoms are nausea, fatigue, vomiting, and diarrhea, which may be followed by epilation, hemorrhage, inflammation of the mouth and throat, and general loss of energy. In severe cases, where the radiation exposure has been relatively large, death may occur within 2 to 4 wk. Those who survive 6 wk after the receipt of a single large dose of radiation may generally be expected to recover.

alpha particle. A positively charged particle ejected spontaneously from the nuclei of some radioactive elements. It is identical to a helium nucleus that has a mass number of 4 and an electrostatic charge of +2.

amenorrhea. Absence or cessation of the menses.

aqueous flare. During a slit lamp test, which focuses on the aqueous part of the eye, a flare effect is seen if particles are present in the eye. These particles can either be debris or they may represent an infection due to ocular damage.

ataxia. Inability to coordinate the muscles in the execution of voluntary movement.

becquerel (Bq). A unit of nuclear disintegration rate. A becquerel is one nuclear disintegration per second.

beta particle. A charged particle emitted from a nucleus during radioactive decay, with a mass equal to 1/1837 that of a photon. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron. Large amounts of beta radiation may cause skin burns, and beta emitters are harmful if they enter the body. Beta particles are easily stopped by a thin sheet of metal or plastic.

carcinogenesis. The origin or production of cancer.

cataractogenesis. The state of cataract formation.

cataract. Loss of transparency of the lens of the eye.

coagulation. Clotting; the process of changing from a liquid to a solid, said especially of blood.

conjuctivitis. Inflammation of the mucous membrane that lines the inner surface of the eyelids and is continued over the forepart of the eyeball.

contamination, radioactive. The presence of radioactive matter in or on a substance where it is unwanted.

Curie (Ci). A unit of activity, or the degree of radioactivity of a radioactive substance. One curie equals 3.7×10^{10} becquerels.

cutaneous. Relating to the skin.

cytogenetic. Genetics relating to the structure and function of the cell, especially the chromosomes.

cytopenia. Reduction of cellular elements in the circulating blood.

denaturation. The process of being made unnatural or changed from the normal in any of its characteristics; often applied to proteins or nucleic acids that are heated or otherwise treated to the point where tertiary structural characteristics are altered.

dermal. Dermatic, dermatoid; dermic; relating to the skin.

dose, absorbed. The amount of energy imparted by nuclear (or ionizing) radiation to unit mass of absorbing material. The unit is the rad. In current usage, the rad unit has been replaced by the SI unit, the gray (Gy; 1 Gy = 100 rad).

dose, acute radiation. Total ionizing radiation dose received at one time and over a period so short that biological recovery cannot occur.

dose equivalent. The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are rem or sievert.

electric field. A fundamental component of electromagnetic (EM) wave, which exists when there is a voltage difference between to points in space.

electric field strength (E). The magnitude of the electric field expressed in volts per meter (V/m).

edema. An accumulation of an excessive amount of watery fluid in cells, tissues, or serous cavities.

electroencephalogram (EEG). Shows electric potential of the brain.

emesis. Vomiting.

enteritis. Inflammation of the intestine, especially of the small intestine.

epithelial. Relating to or consisting of epithelium.

epithelium. The purely cellular avascular layer covering all the free surfaces, cutaneous, mucous, and serous, including the glands and other structures derived therefrom.

erythema. Inflammatory redness of the skin.

external exposure. Irradiation comes from sources outside the body.

far-field region. The region far enough from an antenna that the power per unit area decreases with the square of the range. In the far-field region, the field has predominantly plane-wave character (i.e., uniform distributions of electric and magnetic fields in planes transverse to the direction of propagation).

fluence. The energy density of the EMF when integrated over the duration of the exposure, usually expressed in units of joules per square centimeters (J/cm^2).

fractionation. The process by which a large radiation dose is received in parts with delays (e.g. 1 d) in between each exposure.

gamma radiation. High-energy, short wavelength electromagnetic radiation (packet of energy) emitted from the nucleus. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best stopped or shielded against by dense materials, such as lead or uranium. Gamma rays are similar to X rays, but are usually more energetic.

gastrointestinal. Gastroenteric; relating to the stomach and intestines.

gastrointestinal syndrome. Acute radiation syndrome symptoms that are related to the gastrointestinal tract.

gonadotropin. Gonadotropic hormone; a hormone capable of promoting gonadal growth and function.

gray. The International System unit of absorbed dose, equal to the energy imparted by ionizing radiation to a mass of matter corresponding to one joule per kilogram. Symbolized Gy.

half-life. The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Measured half-lives vary from millionths of a second to billions of years. Also called physical half-life.

hardness. A measure of the ability of a system to withstand exposure to one or more effects of man-made hostile environments.

hematological. That which relates to blood and/or blood-forming organs.

hematological syndrome. Acute radiation syndrome symptoms that are related to the hematological system.

hemopoietic. That which relates to blood cells.

hematochezia. Passage of bloody stools.

heroic treatment. Extensive medical treatment of a patient who suffers from acute radiation syndrome. This may include antibiotics treatment and bone-marrow transplants.

hertz (Hz). The unit for expressing frequency. One hertz is equivalent to one cycle per second.

human resonance range. The frequency region where absorption of RF energy in the body is enhanced. For sizes ranging from a baby to an adult, peak absorption varies depending on the individual's size relative to the wavelength and orientation relative to the polarization of the wave. The PELs have been established to cover the range in human sizes, shapes, and positions.

hyperesthesia. Abnormal acuteness of sensitivity to touch, pain, or other sensory stimuli.

incandescence. The quality or state of being white, glowing, or luminescent with intense heat.

internal exposure. Irradiation comes from sources inside the body.

interstitial. Relating to spaces within a tissue or organ, but excluding such spaces as body cavities or potential space.

intragastric. Within the stomach.

keratinocyte. A cell of the living epidermis and certain oral epithelium that produces keratin in the process of differentiating into the dead and fully keratinized cells of the stratum corneum.

lethal dose (LD_x). The lethal whole body dose for x% of the population to die in 60 d. The value for this without treatment is 3.45 Gy.

leukocyte. White blood cell.

lymphocyte. Lymph cell; lympholeukocyte; a white blood cell formed in lymphatic tissue throughout the body and in normal adults comprising approximately 22 to 28% of the total number of leukocytes in the circulating blood.

lymphopenia. Reduction in the number of lymphocytes in the circulating blood.

magnetic field. A fundamental component of EM waves produced by a moving electric charge.

magnetic field strength (H). The strength of the magnetic field expressed in amps per meter (A/m).

malaise. A feeling of general discomfort or uneasiness, as an out-of-sorts feeling.

mean lethal dose. The lethal whole body dose for 50% of the population.

meiosis. Meiotic division; the special process of cell division that results in the formation of gametes, consisting of two nuclear divisions in rapid succession that result in the formation of four gametocytes, each containing half the number of chromosomes found in somatic cells.

near-field region. A region generally in close proximity to an antenna or other radiating structure in which the electric and magnetic fields do not exhibit a plane-wave relationship, and the power does not decrease with the square of distance from the source but varies considerably from point to point. The near-field region is further subdivided into the reactive near field, which is closest to the radiating structure and contains most or nearly all of the stored energy, and the radiation near field, where the radiating field predominates over the reactive field but lacks substantial plane-wave character and is complicated in structure. For most antennas, the outer boundary of the reactive near-field region is considered to occur at a distance of one-half wavelength from the antenna surface.

necrosis. The pathologic death of one or more cells, or a portion of tissue or organ, resulting from irreversible damage.

neutropenia. The presence of abnormally small numbers of neutrophils in the circulating blood.

oliguria. Scanty urination.

ondansetron. Anti-emetic agent; also causes no drowsiness.

oocyte. Ovocyte; the immature ovum.

oropharyngeal. Relating to the oropharynx.

paraesthesia. An abnormal sensation, such as of burning, pricking, tickling, or tingling.

percutaneous. Diadermic; transcutaneous; transdermic; denoting the passage of substance through unbroken skin, as in absorption by inunction.

permissible exposure limit (PEL). Limits for RF exposure established for the protection of personnel. There are no expectations that any adverse health effects will occur with exposures that are within the PEL, even under repeated or long-term exposure conditions.

petechiae. Minute hemorragic spots, of pinpoint to pinhead size.

photokeratitis. Inflammation of the cornea to laser light.

photon. A quantum (or packet) of energy emitted in the form of electromagnetic radiation. Gamma rays and X rays are examples of photons.

photosensitivity. Circumstance where the skin is sensitive to light.

plane wave. An EM wave characterized by mutually orthogonal electric and magnetic fields that are related by the impedance of free space (377 ohms). For plane waves, power density (S), electric field strength (E), and magnetic field strength (H) exhibit the following relationship: $S = E^2/3700 = 37.7 * H^2$, where S is in mW/cm^2, E is in V/m, and H is in A/m.

plane-wave-equivalent power density. The magnitude of power density that would exist for an EM wave in free space having the same electric or magnetic field strengths.

power density (S). The rate of energy transported into a small sphere divided by the cross-sectional area of that sphere. It is expressed in units of W/m^2.

progenitor. A precursor, ancestor; one who begets.

purpura. A condition characterized by hemorrhage into the skin. The color is first red, gradually darkens to purple, fades to a brownish yellow, and usually disappears in 2 or 3 wk.

quality factor (QF). The modifying factor that is used to derive dose equivalent from absorbed dose.

rad. The special unit of absorbed dose. One rad is equal to an absorbed dose of 100 ergs/gram or 0.01 J/kg (0.01 gray).

radiant exposure. Total thermal energy incident per unit area; it is usually expressed in units of J/cm^2.

radio frequency (RF). The RF region is defined as extending from 3 kHz to 300 GHz.

radioisotope. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. Approximately 5000 natural and artificial radioisotopes have been identified.

radionuclide. A radioisotope.

rem. A unit of ionizing radiation, equal to the amount that produces the same damage to humans as one roetgen of high-voltage x-rays. Derived from roentgen equivalent man.

re-radiated field. EMF resulting from currents induced in a secondary, predominantly conducting object by EM waves incident on that object from one or more primary radiating structures or antennas. Re-radiated fields are sometimes called reflected or scattered fields. The scattering object is sometimes called a re-radiator, or a secondary or parasitic radiator.

retinal lesion. Pathological change in the retina.

roentgen (R). A unit of exposure to ionizing radiation. It is that amount of gamma or X rays required to produce ions carrying 1 electrostatic unit of electrical charge in 1 cm^3 of dry air under standard conditions. Named after Wilhelm Roentgen, the German scientist who discovered X rays in 1895.

roentgen equivalent man (rem). The special unit of any of the quantities expressed as dose equivalent. The dose equivalent in rem is equal to the absorbed dose in rad multiplied by the quality factor (1 rem = 0.01 sievert).

seivert (Sv). The unit of any of the quantities expressed as dose equivalent. The dose equivalent in sieverts is equal to the absorbed dose in gray multiplied by the quality factor (1 Sv = 100 rem).

specific absorption. The amount of energy absorbed over an exposure time period. It is expressed in units of joules per kilogram (J/kg).

specific absorption rate (SAR). The time derivative of the incremental energy (dW) absorbed by an incremental mass (dm) contained in a volume (dV) of a given density. SAR is expressed in units of W/kg.

spermatid. A cell in a late stage of the development of the spermatozoon; it is a haploid cell divided from the secondary spermatocyte and evolves by spermatogenesis into a spermatozoon.

spermatocytes. Parent cell of a spermatid, derived by mitotic division from a spermatogonium.

spermatogenesis. The entire process by which spermatogonial stem cells divide and differentiate into spermatozoa.

spermatogonia. Spermatogonium.

spermatogonium. Spermatoblast; spermatogone; the primitive sperm cell derived by mitotic division from the germ cell; increasing several times in size, it becomes a primary spermatocyte.

spermatozoa. Sperms, sperm cells.

stem cell. A self-sustaining cell that relies on its own self-maintenance for its continued existence. All progeny depend on the continued existence of the stem cell pool.

stomatitis. Inflammation of the mucous membrane of the mouth.

subacute syndrome. Less marked in severity or duration than acute radiation syndrome.

supportive treatment. There are four basic aspects of supportive treatment. These are the maintenance of a clean environment, prophylactic oropharyngeal and gastrointestinal antibiotic therapy, use of intravenous fluid,

nutrients, and blood fractions, and finally, vigorous therapy of infections.

thermal cataract. Cataract formed due to radiation exposure.

thrombopenia. A condition in which there is an abnormally small number of platelets in the circulating blood.

vacuoles. A minute space in any tissue.

vesiculation. Blistering; vesication; the formation of vesicles.

whole body exposure. Irradiation of the whole body or most of the body volume. It is usually an acute exposure.

xerostomia. Dryness of the mouth, having a varied etiology, resulting from diminished or arrested salivary secretion, or asialism.

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